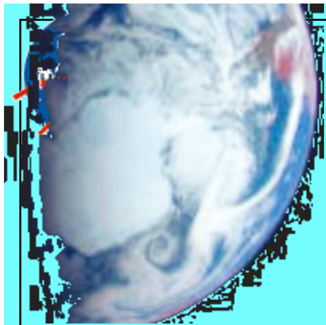
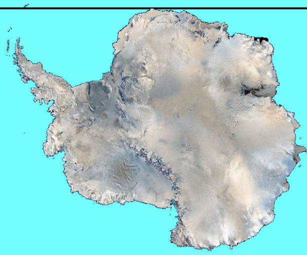
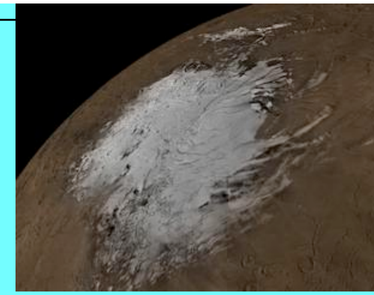
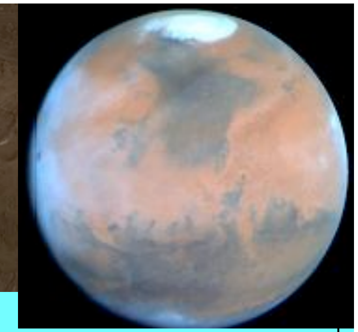








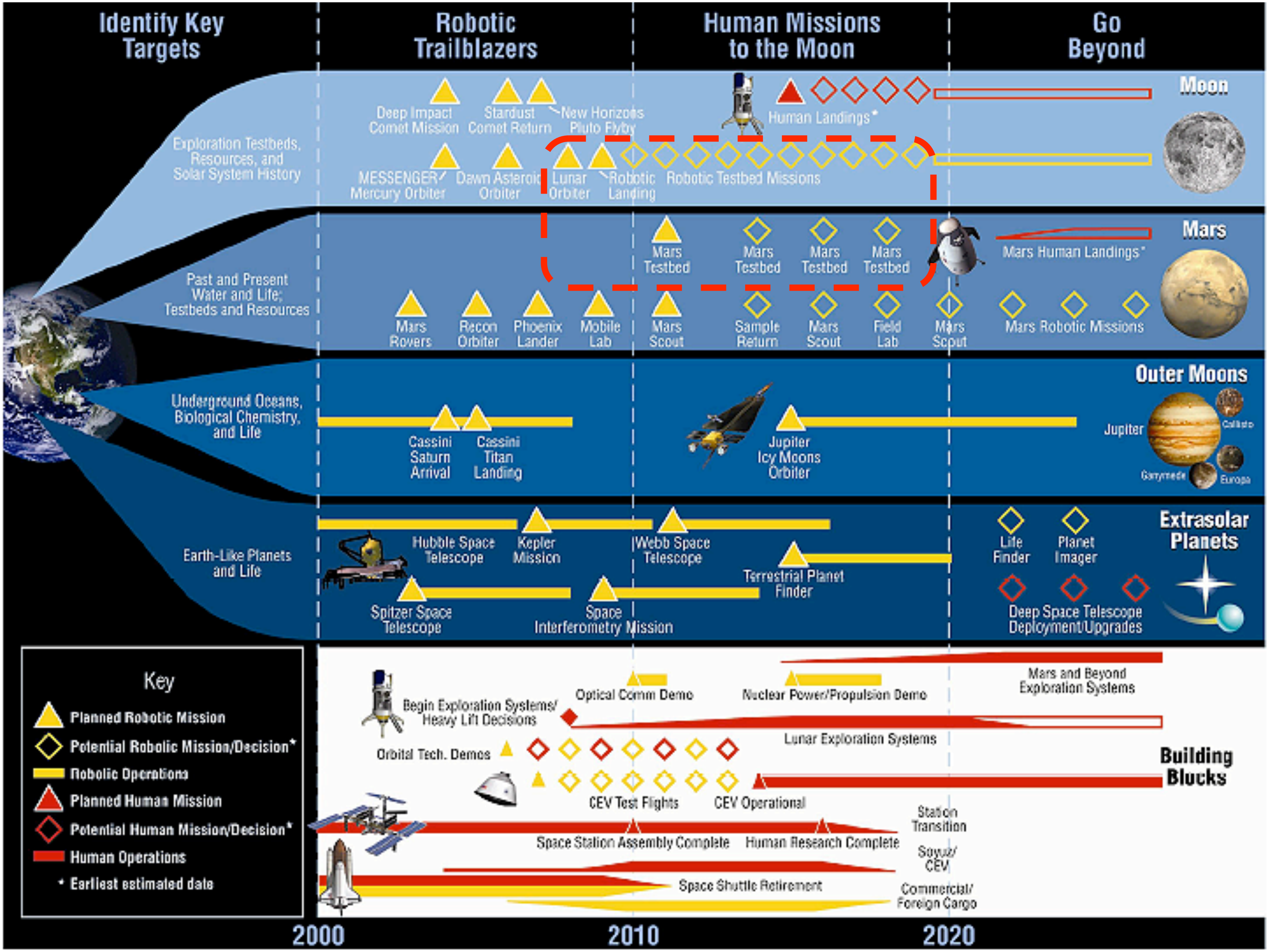
Exploration Systems and Technologies

Tony Freeman

Stacey W. Boland

Paul Digiacomo

September 2005

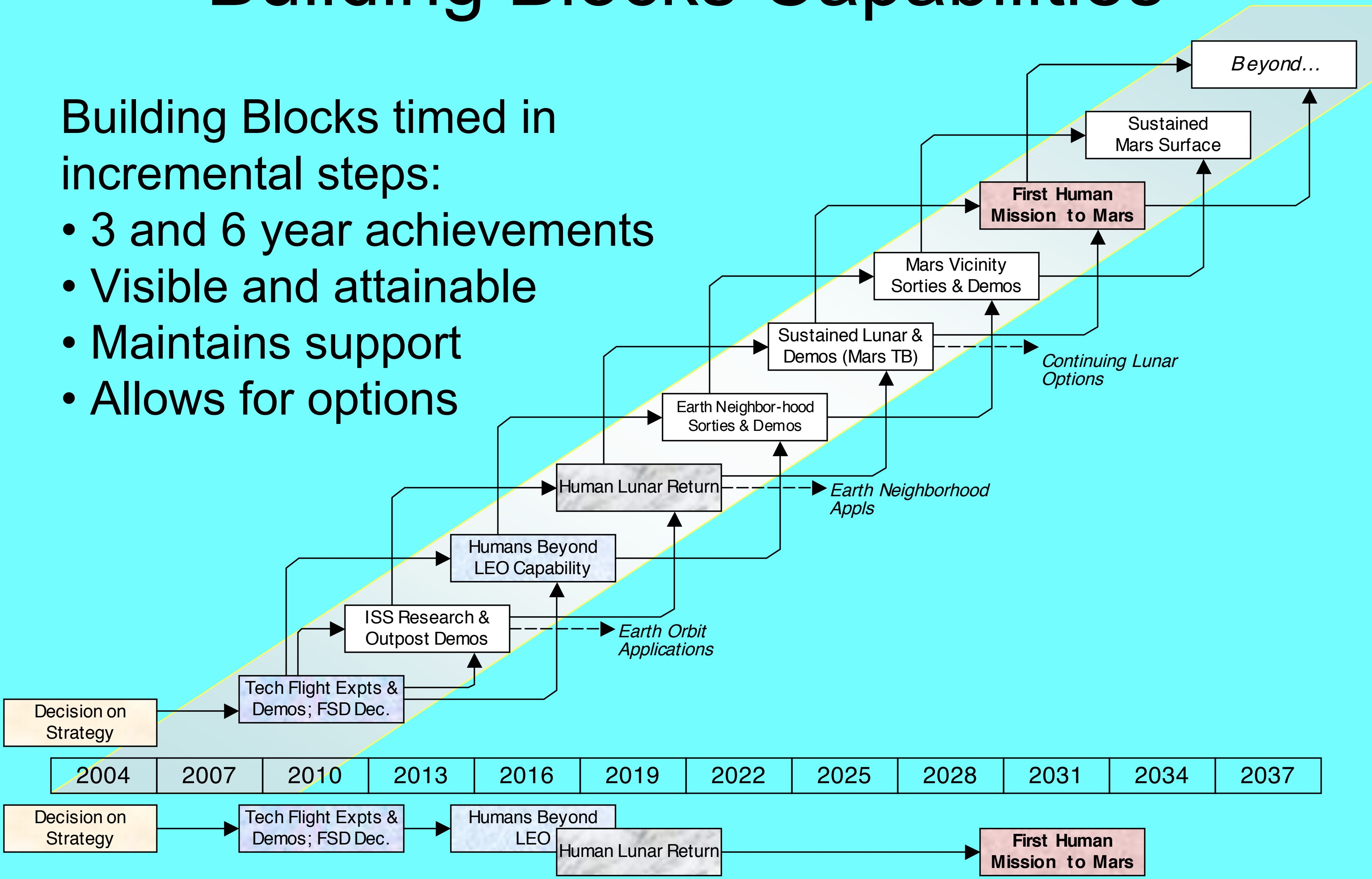

Identify Key Targets
Robotic Trailblazers
Human Missions to the Moon
Go Beyond
Moon
Deep Impact Comet Mission
Stardust Comet Return
New Horizons Pluto Flyby
Human Landings*
Exploration Testbeds, Resources, and Solar System History
MESSENGER Mercury Orbiter
Dawn Asteroid Orbiter
Lunar Orbiter
Robotic Landing
Robotic Testbed Missions
Mars
Mars Testbed
Mars Testbed
Mars Testbed
Mars Testbed
Mars Human Landings*
Past and Present Water and Life; Testbeds and Resources
Mars Rovers
Recon Orbiter
Phoenix Lander
Mobile Lab
Mars Scout
Sample Return
Mars Scout
Field Lab
Mars Scout
Mars Robotic Missions
Outer Moons
Underground Oceans, Biological Chemistry, and Life
Cassini Saturn Arrival
Cassini Titan Landing
Jupiter Icy Moons Orbiter
Jupiter
Callisto
Ganymede
Europa
Extrasolar Planets
Earth-Like Planets and Life
Hubble Space Telescope
Kepler Mission
Webb Space Telescope
Terrestrial Planet Finder
Life Finder
Planet Imager
Spitzer Space Telescope
Space Interferometry Mission
Deep Space Telescope Deployment/Upgrades
Key
Planned Robotic Mission
Potential Robotic Mission/Decision*
Robotic Operations
Planned Human Mission
Potential Human Mission/Decision*
Human Operations
* Earliest estimated date
Mars and Beyond Exploration Systems
Begin Exploration Systems/ Heavy Lift Decisions
Optical Comm Demo
Nuclear Power/Propulsion Demo
Lunar Exploration Systems
Orbital Tech. Demos
CEV Test Flights
CEV Operational
Building Blocks
Station Transition
Space Station Assembly Complete
Human Research Complete
Soyuz/ CEV
Space Shuttle Retirement
Commercial/ Foreign Cargo
2000
2010
2020

A Stepping Stone Strategy to Mars

Building Blocks Capabilities

Building Blocks timed in incremental steps:

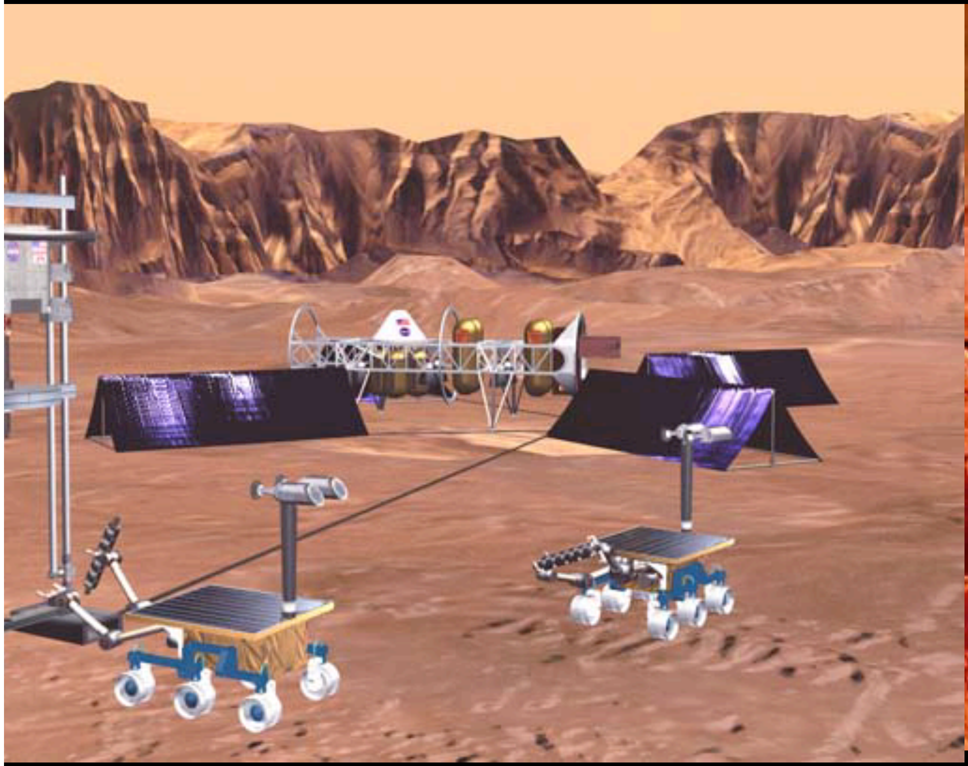
- 3 and 6 year achievements
- Visible and attainable
- Maintains support
- Allows for options

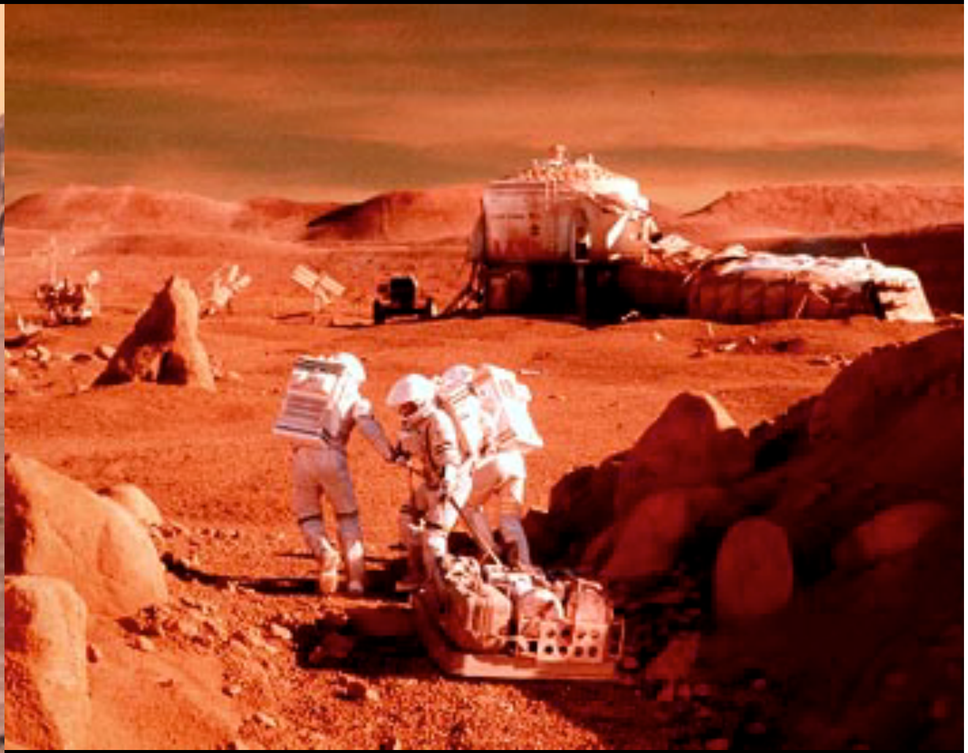


The needs of an Explorer

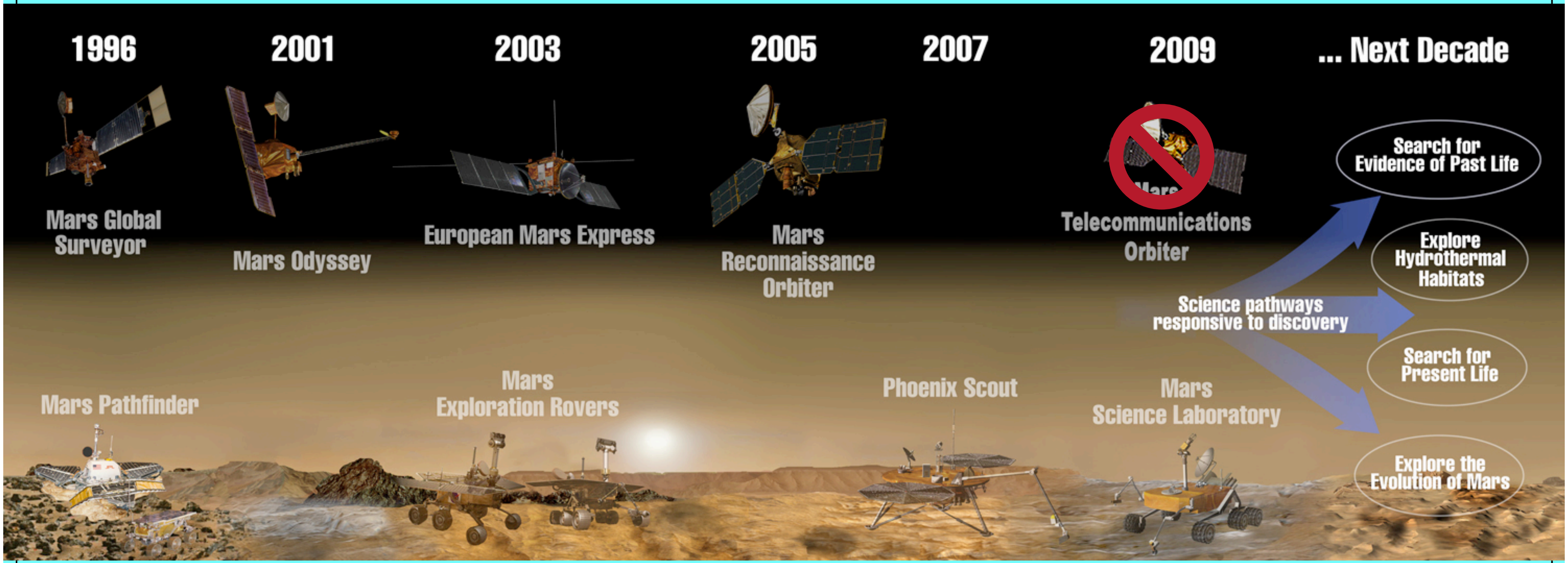
- **Air - to breathe**
- **Power - to run equipment**
- **H_20 - a supply of water**
- **Food**
- **Fuel - to return home**
- **Mobility - to move around**
- **Hazards - warning of and reduced risk of**
- **Communications**

Robotic missions leading to robotic and human Mars outposts in the Vision for Space Exploration





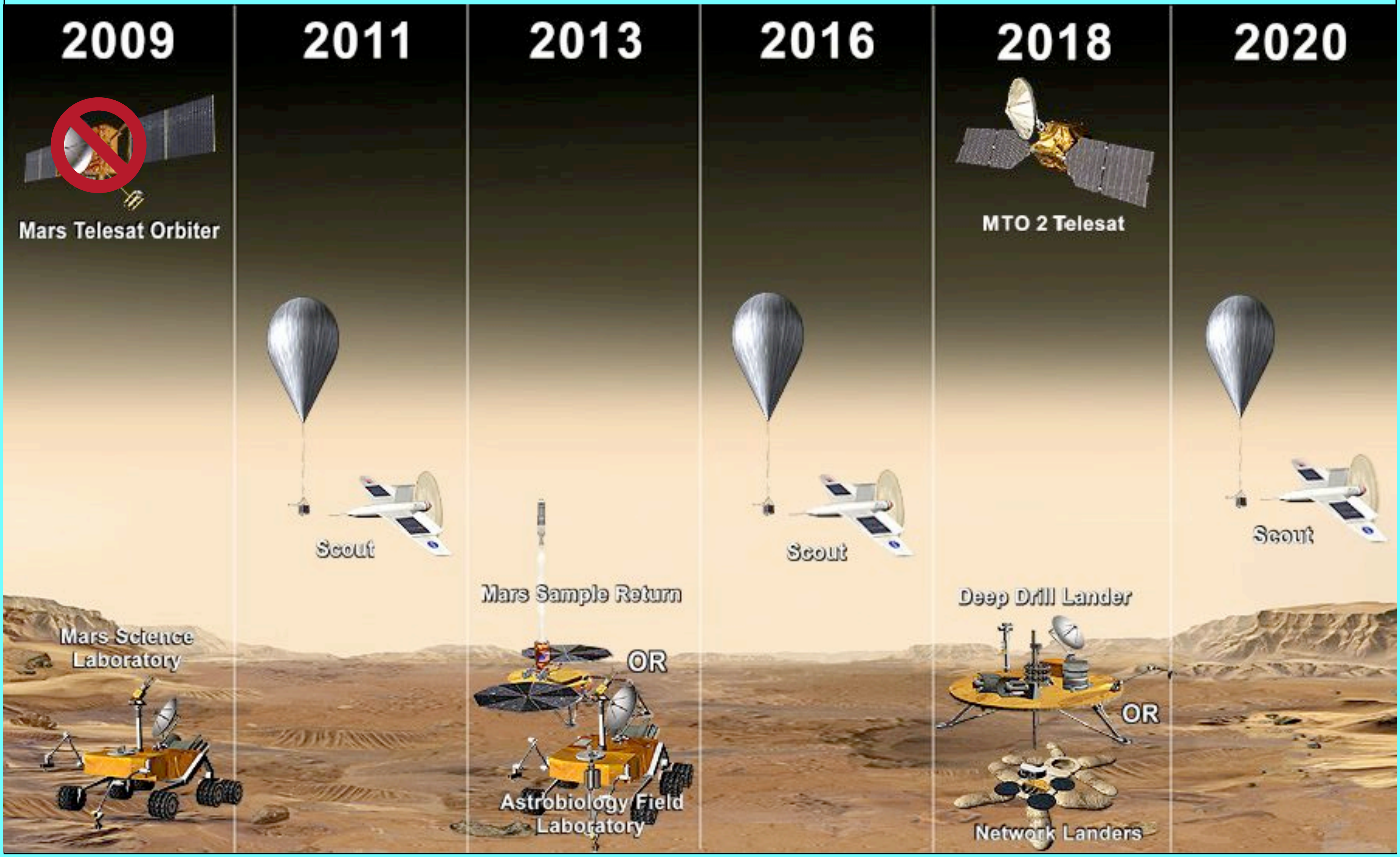
Mars exploration



Believing scientific exploration of Mars should be discovery-driven, the Mars Program created "Investigation Pathways"

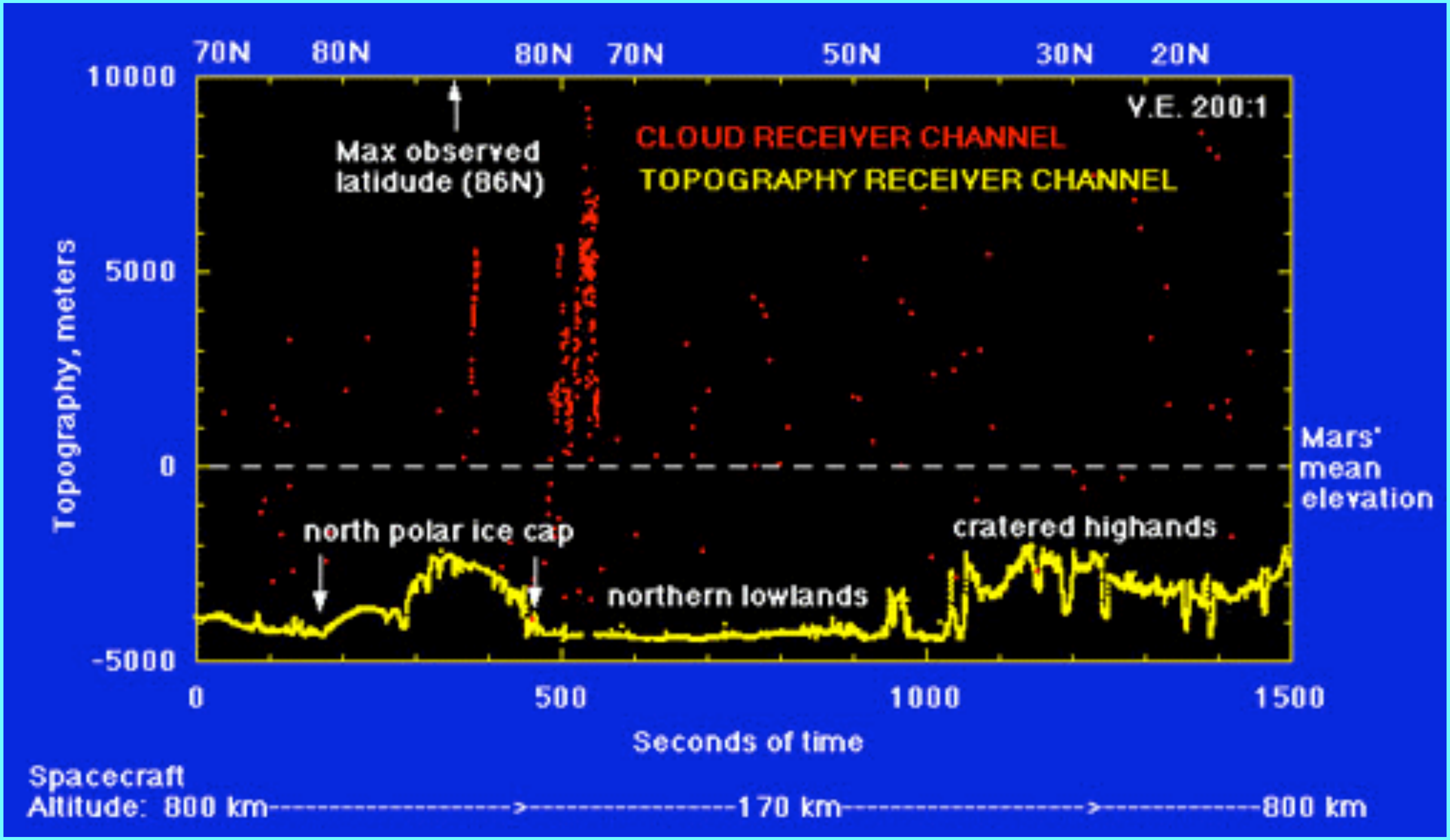
- Illustrates program options
- Exposes mission options
- Identifies long-lead technology requirements.

Mars Exploration Program
Next Decade Timeline



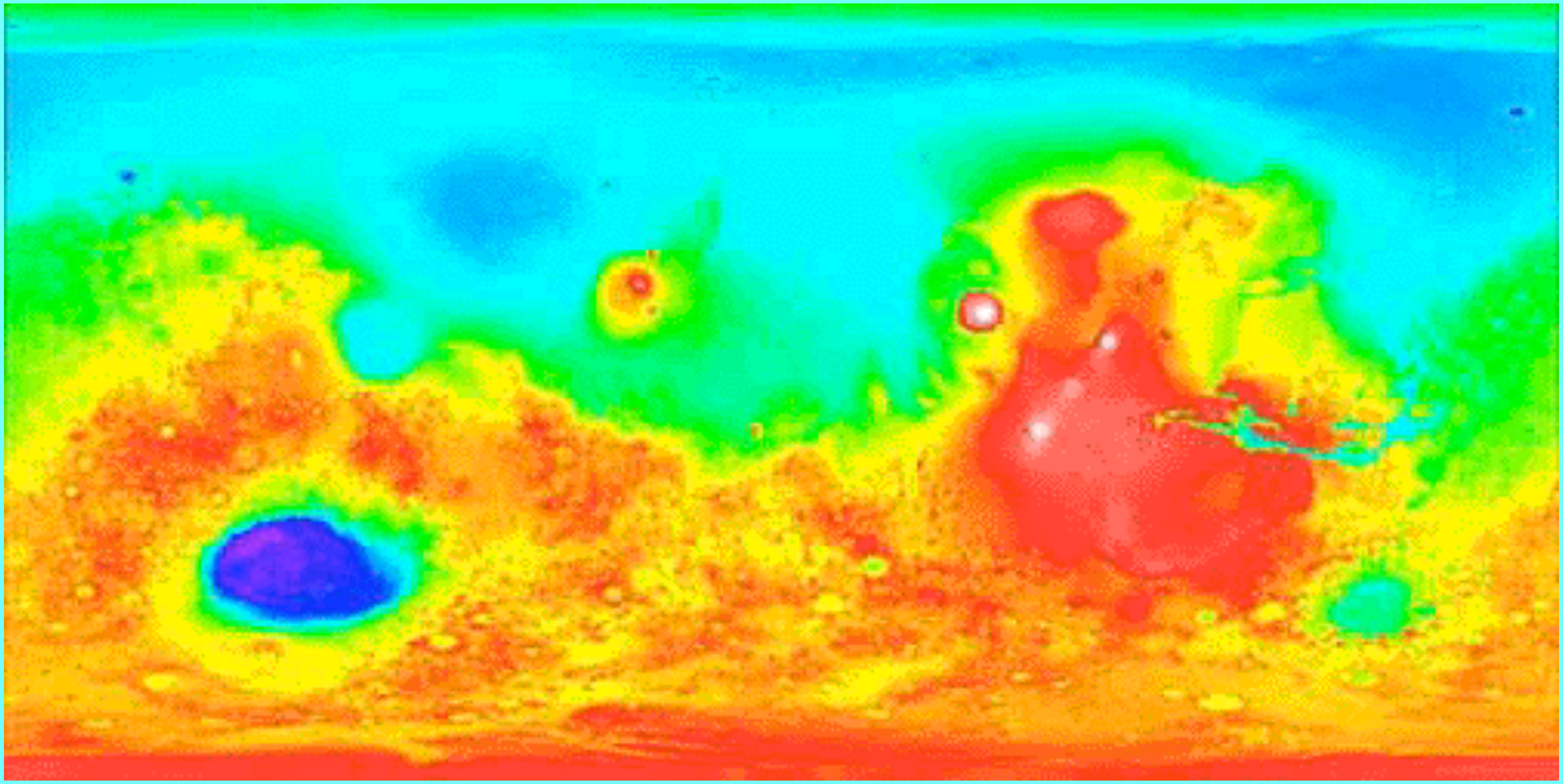
Mars Orbiter Laser Altimeter (MOLA)

Profile over polar ice cap



Mars Orbiter Laser Altimeter (MOLA)

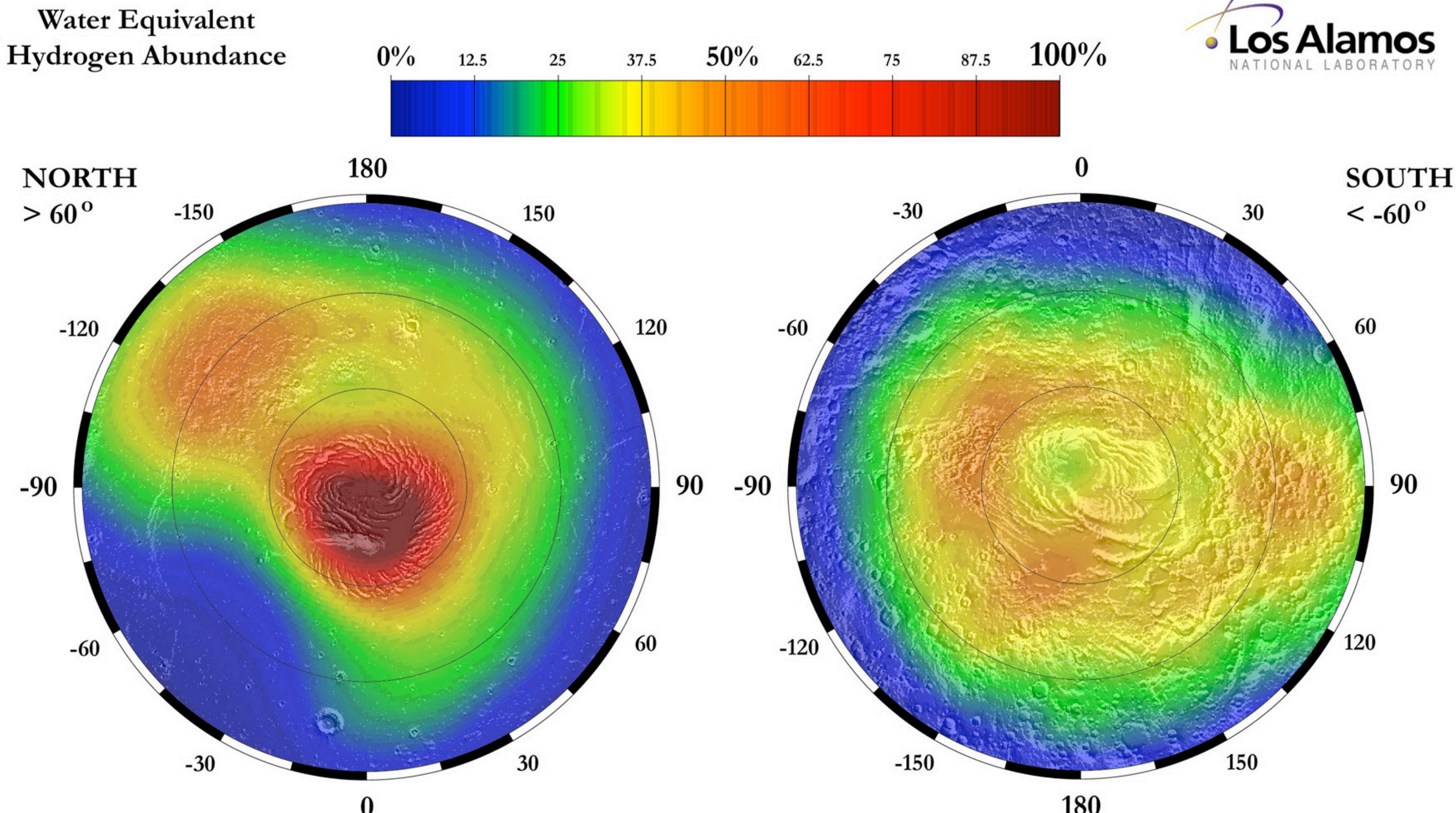
Topographic Map of Mars



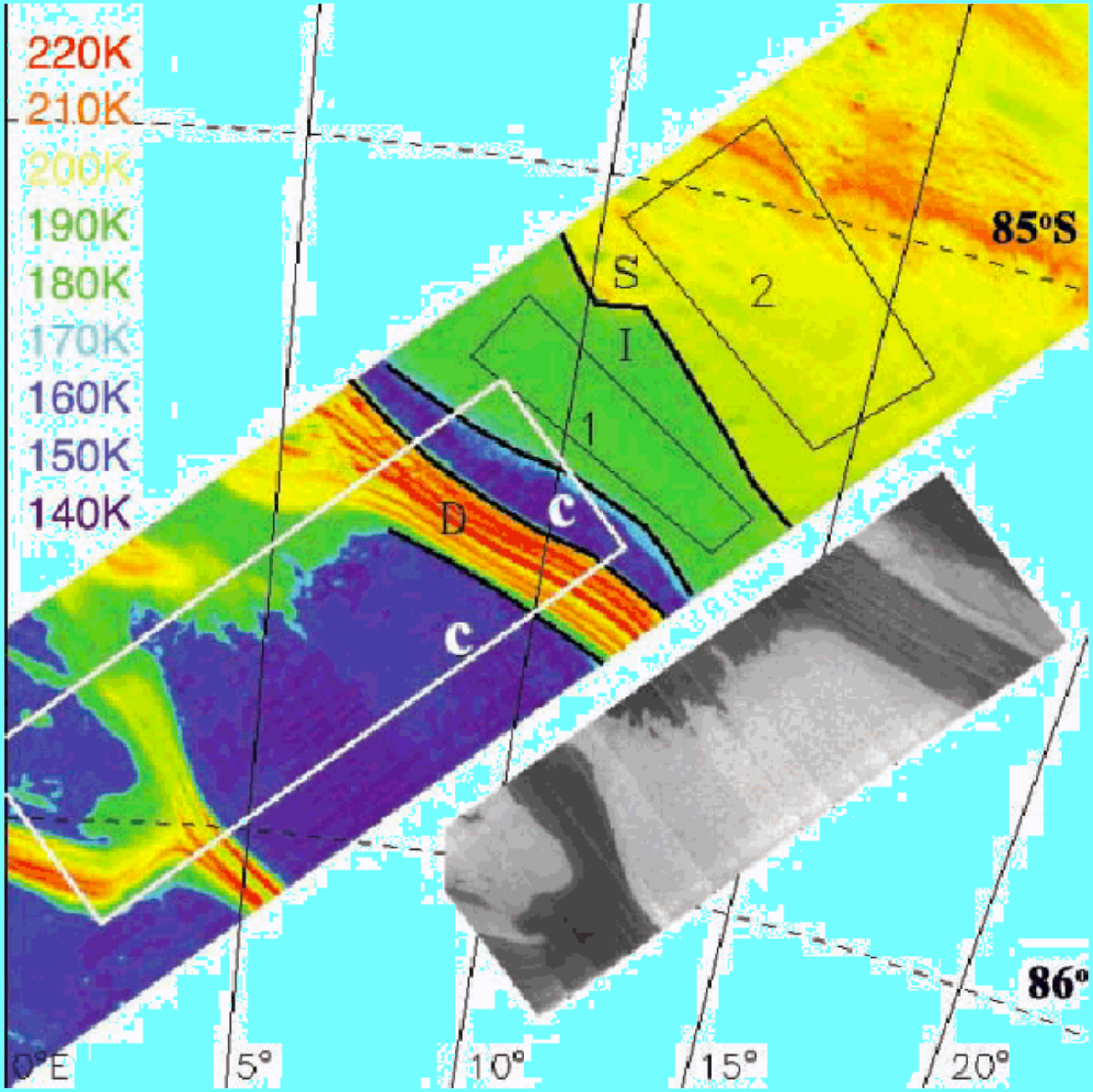
Lower-Limit H_2O Mass Fraction From Neutron Spectrometer

Jet Propulsion Laboratory
California Institute of Technology

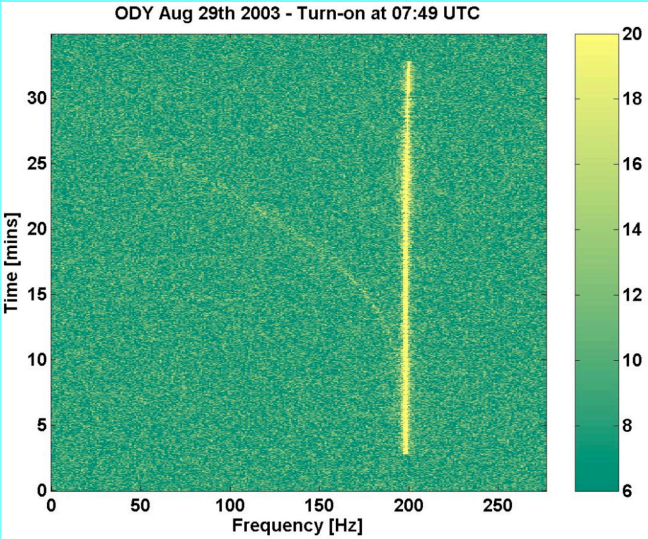
Los Alamos NATIONAL LABORATORY

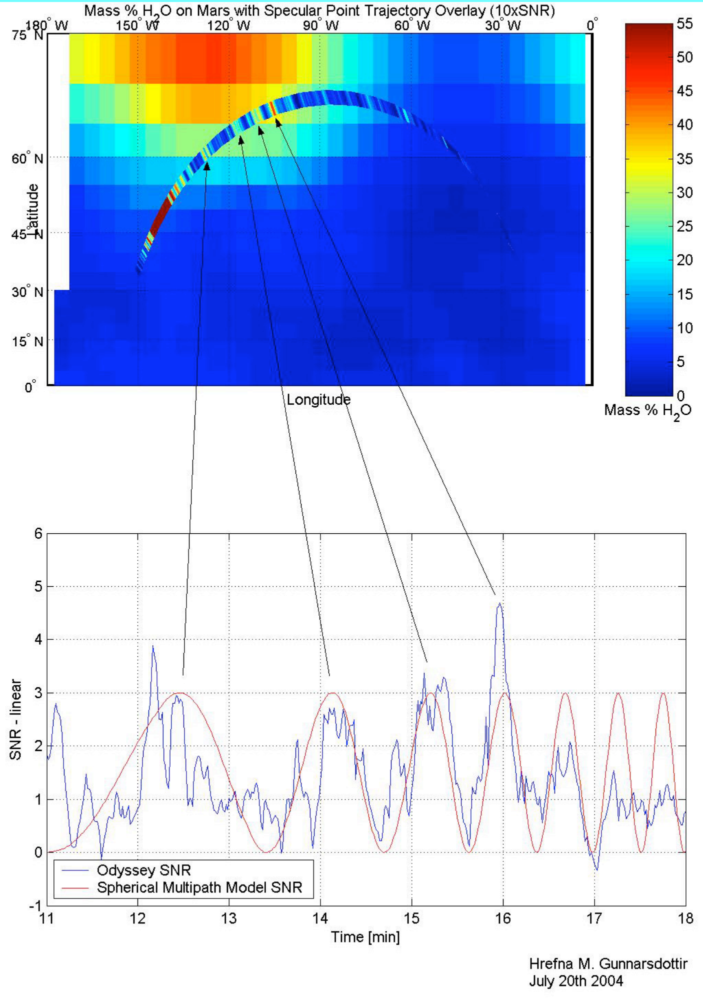


H_2O Ice Exposed at the Surface Near the South Pole



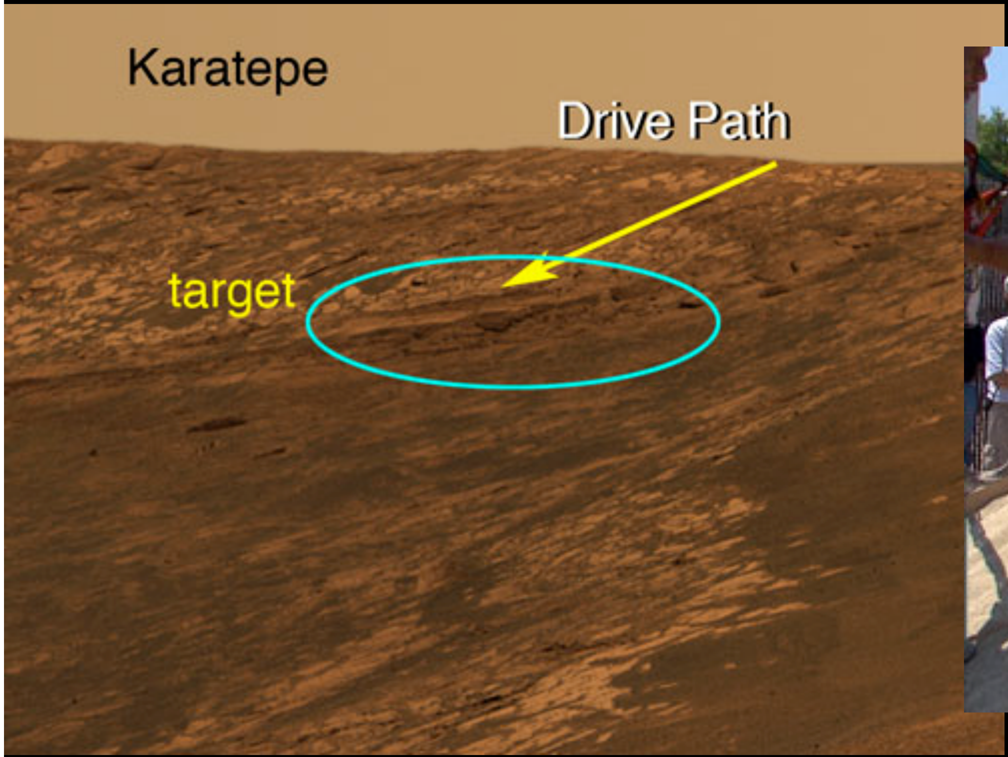
Something Different





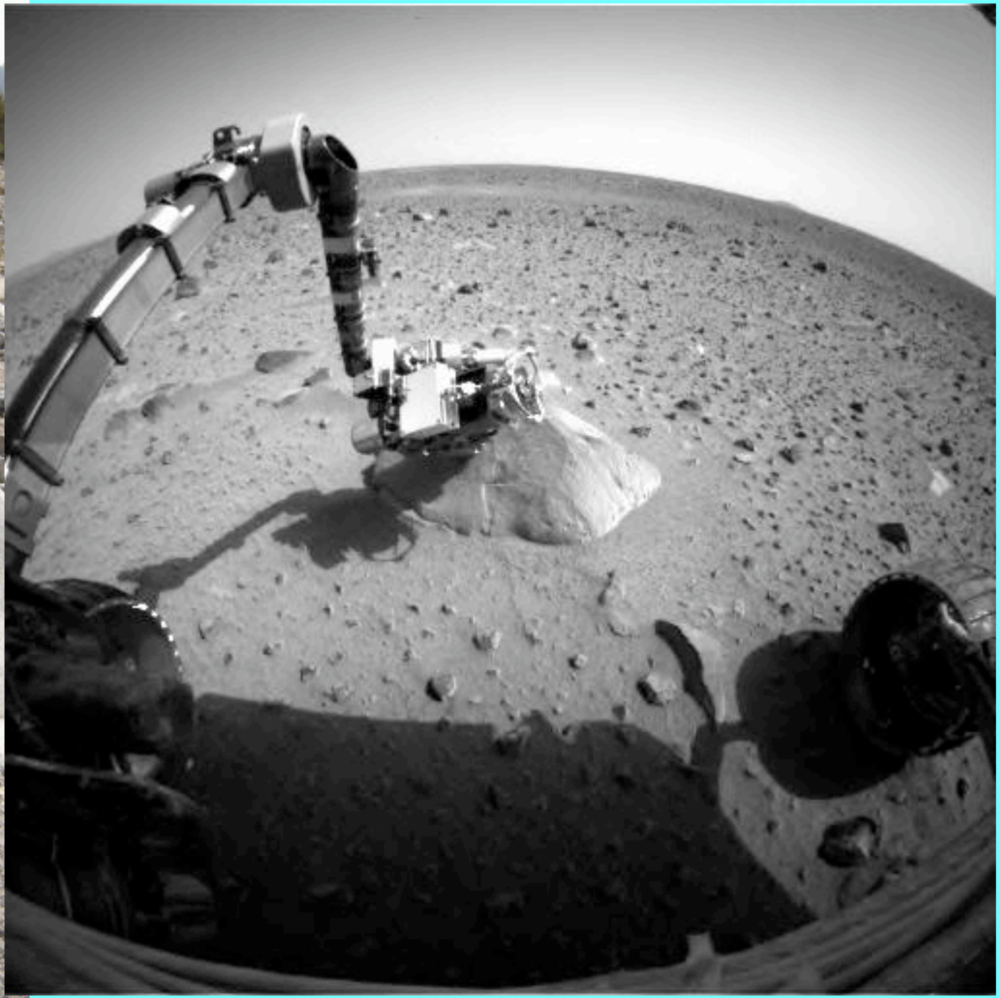
- UHF Radar
- Stanford - Odyssey bistatic observations
  - Proposed after detection of UHF specular echo in UHF system test to support Mars relay.
  - Layered model correlates in an intriguing fashion with ODY neutron spectrometer water mass.
- [*Callas, Linscott, Gunnarsdottir, Simpson*]

Planning and testing to drive *Opportunity* down Karatepe slope in Endurance Crater, June 2004

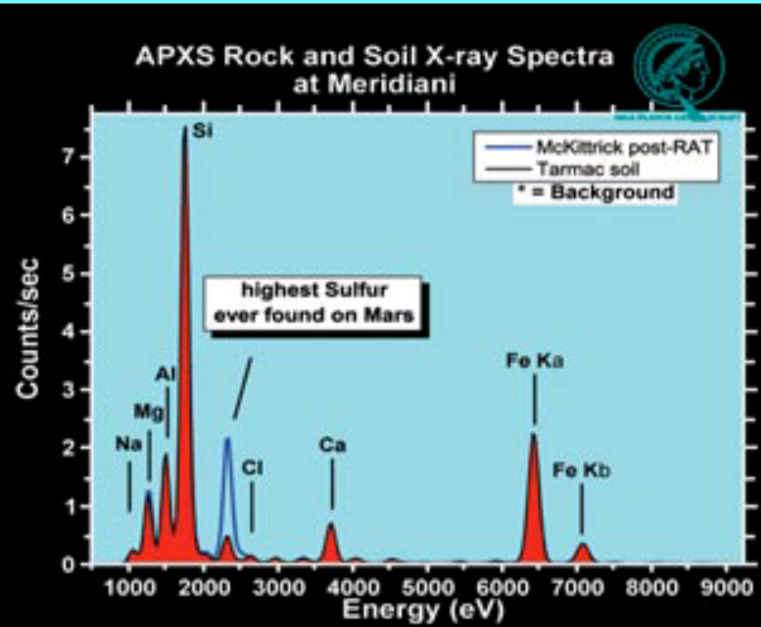


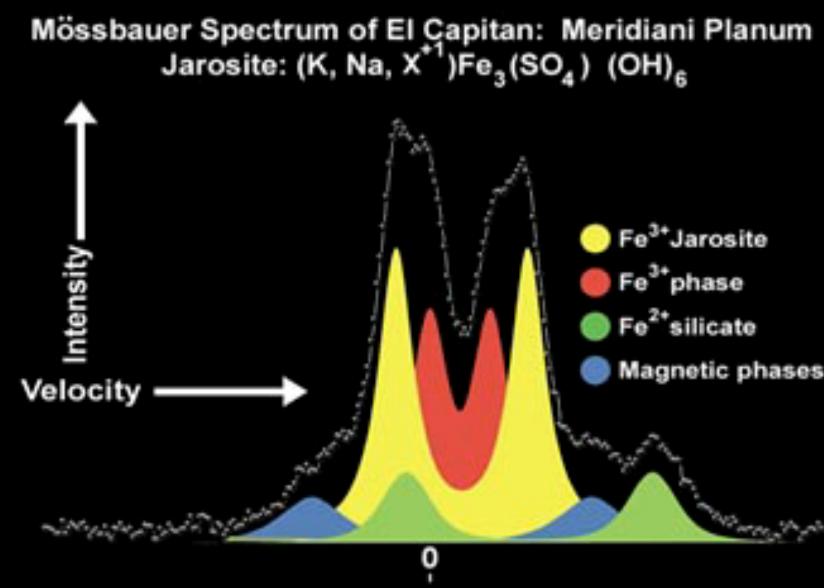
Mars Exploration Rovers in test with 1997 Sojourner rover

Geologists in action



Opportunity spectra



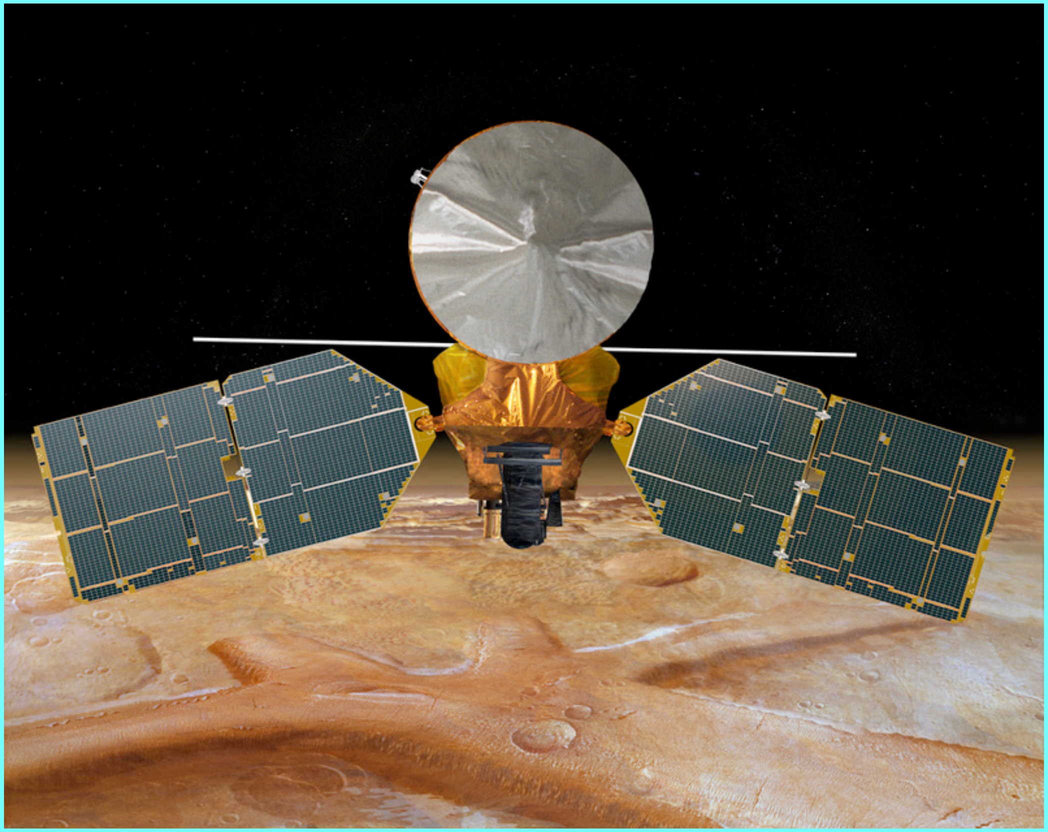


Opportunity APXS spectrum with high sulfur content, implying sulphates and standing water

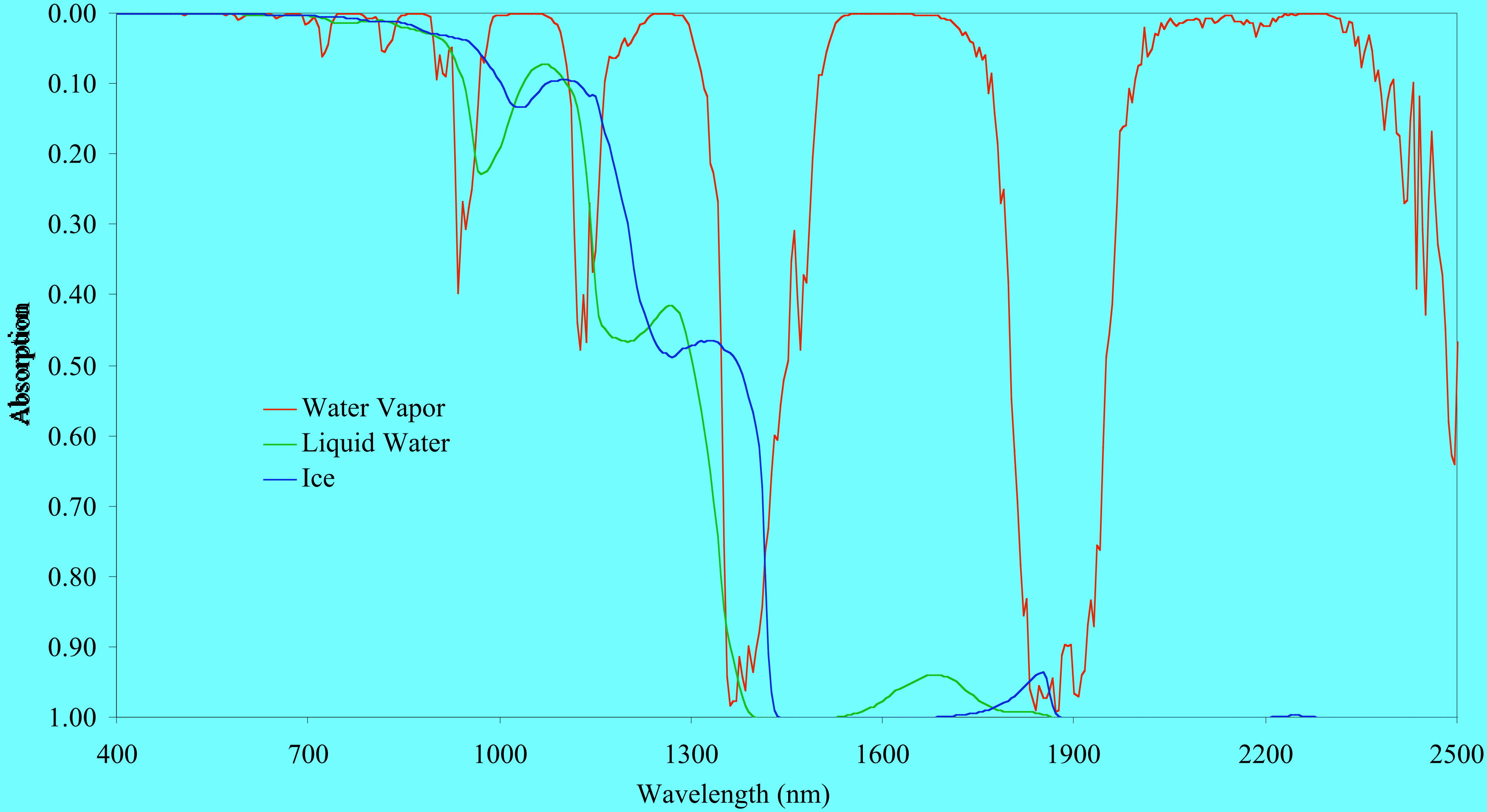
Jarosite with sulphate and hydroxyl components from *Opportunity*, implying evaporation from a salty brine

Mars Reconnaissance Orbiter - launched August 12, 2005

- Study history of water on Mars
- Seek evidence of sub-surface water.
- Seek water-formed minerals.
- Study atmospheric dust and water distribution.
- Monitor daily global weather.
- Three week launch period, August 10-30, 2005.
- 5.6 Mb/s maximum data rate enables 1 meter resolution over large areas.
- Shallow Subsurface Radar (SHARAD) provided by ASI, Alenia Spazio, University of Rome-INFOCOM.



Absorption of Water Vapor, Liquid and Solid in the Solar Reflected Spectrum



The absorption bands of the three phases of water near 1000 nm are overlapping, but displaced

Denali, AK

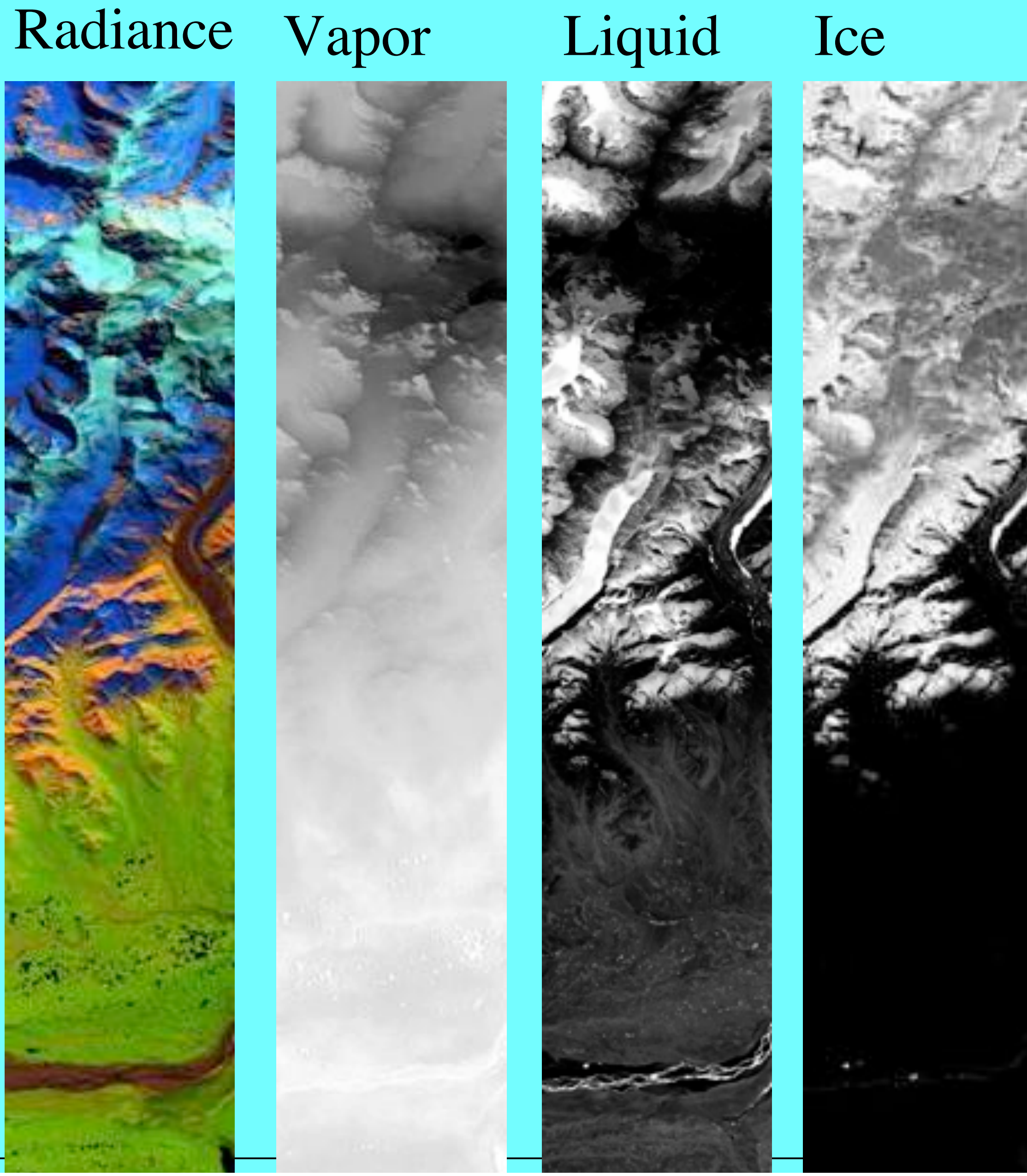


Image Results for the Forward Inversion for the Three Phases of Water

- Water vapor ranges from 0.51 to 12.7 mm precipitable water
- Liquid water ranges from 0 to 7.4 mm equivalent path transmittance
- Ice ranges from 0 to 27.9 mm equivalent path transmittance

Ice, Liquid Water and Water Vapor as Red, Green, Blue Image

Blue displays water vapor. Water vapor is highest in the lower elevations.

Green displays liquid water. Liquid water occurs both as vegetation leaf water and melting snow.

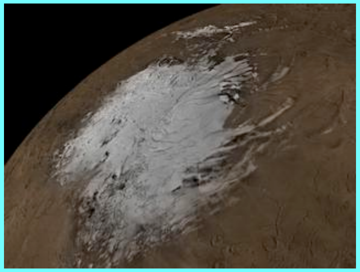
Red displays ice. Non melting snow and ice occurs at high elevation.

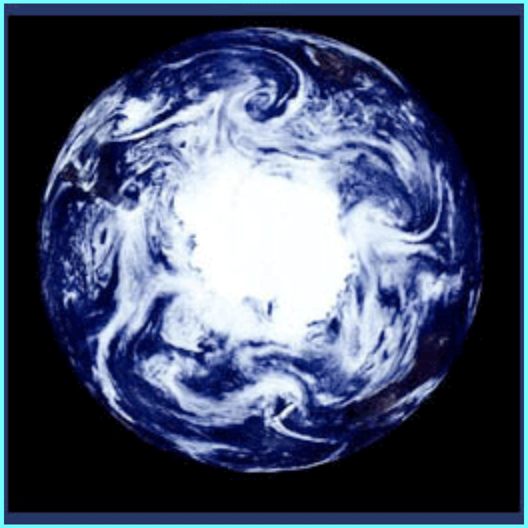
Areas that are cyan are high in water vapor and high in vegetation liquid water.

Areas that are yellow are high in liquid water and high in ice. These are melting snow regions.

Earth & Mars at the Poles

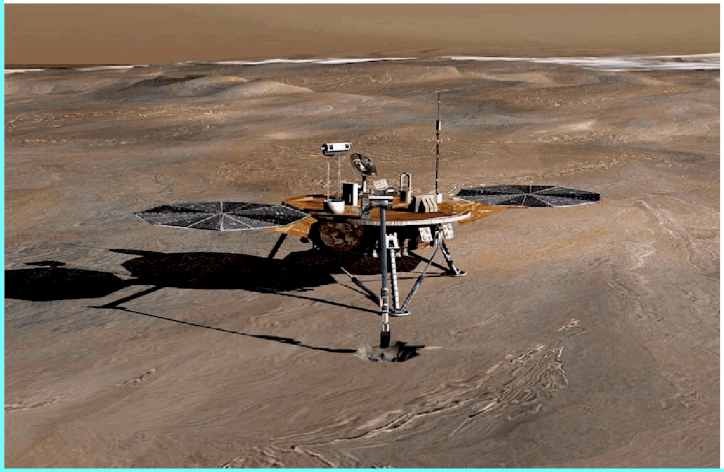
- Mars Phoenix Mission
  - Launch in '-07, land in March 2008
  - EOI Submitted to IPY for Antarctic field experiment



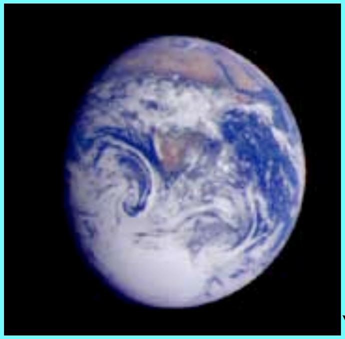


Phoenix Lander

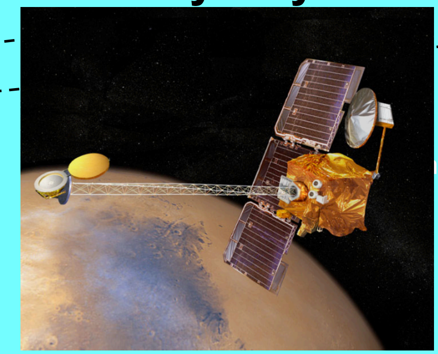
- Phoenix will be the first time that the polar regions on Mars will have been investigated in-situ. All measurements will provide the benchmark for future exploration.
- Phoenix will push the frontier of polar science from Earth-based to solar system-based.
- Phoenix directly enhances the polar observational capability within the solar system, while still complementing the knowledge gain in the Earth's polar regions.



Demonstrated Benefits of Relay Orbiters



Odyssey



MGS

Direct-to-Earth

- 30 Mbits/sol
- 1 watt-hour/Mbit
- < 1 bps semaphores

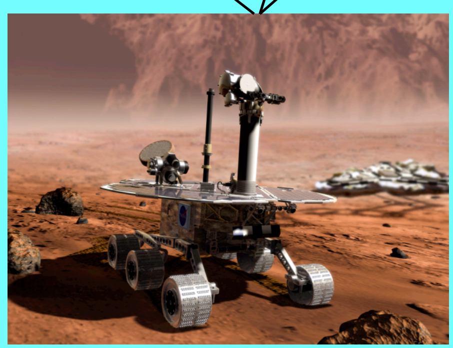
Increased data return

Improved energy efficiency

EDL telemetry

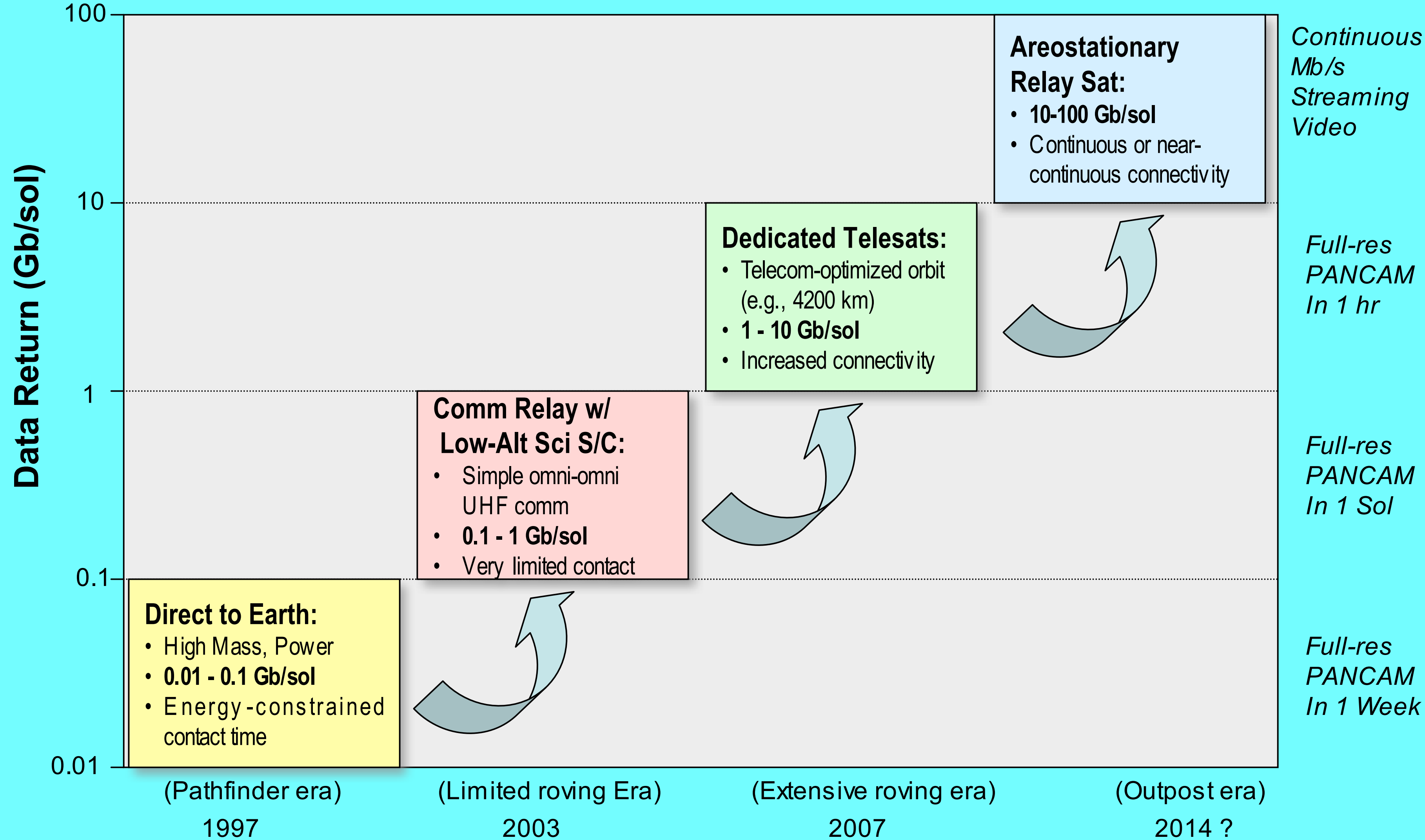
Relay

- 150 Mbits/sol
- 0.1 watt-hour/Mbit
- 8 kbps telemetry

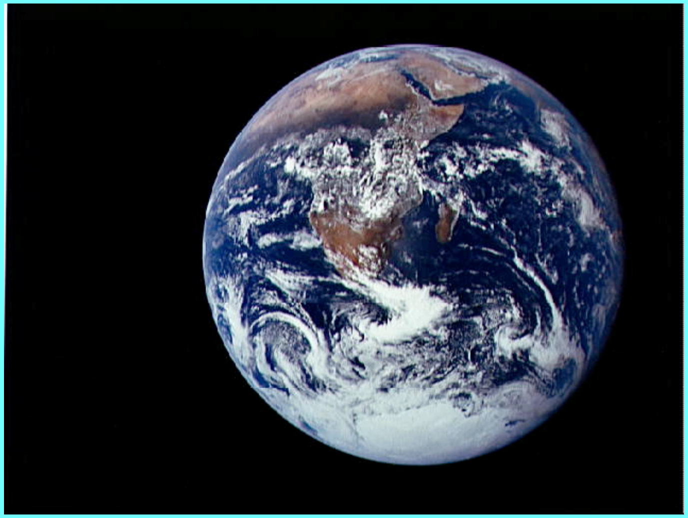


Odyssey and MGS have returned over 91% of the MER data

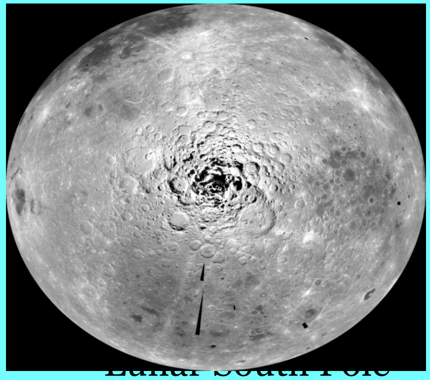
Evolution of Mars Telecommunications Capability



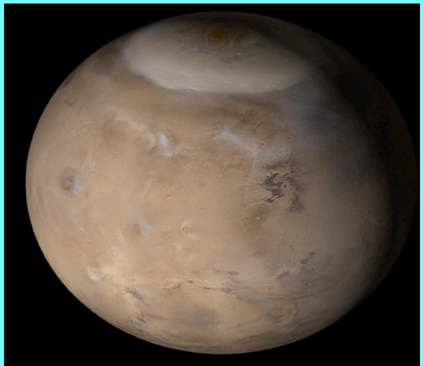
TODAY: Polar regions of Planets are key to future Exploration Vision → IPY relevance



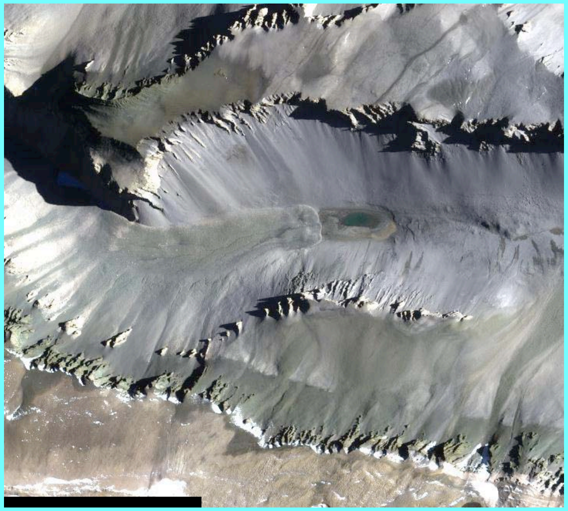
Earth's Polar regions



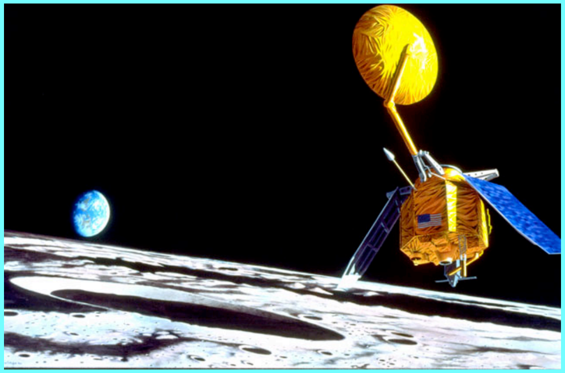
Lunar South Pole



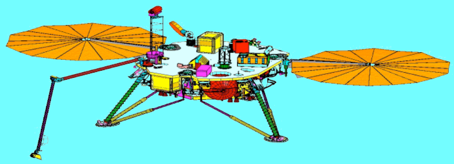
Mars: Polar Water



Dry Valleys, Antarctica



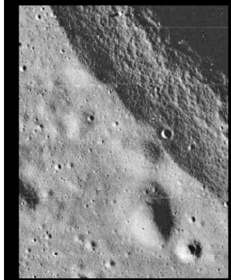
2008 **LRO** focus on Poles



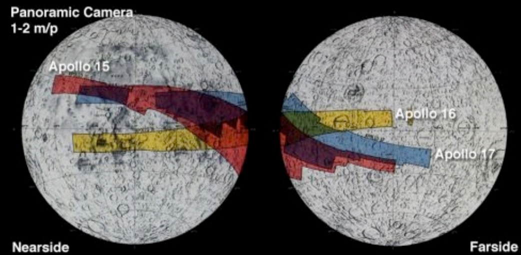
Phoenix 2008 at N. Pole
History of water and polar climate on Mars

2008 Lunar Reconnaissance Orbiter:

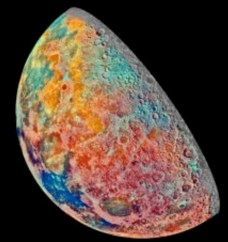
First Step in the Lunar Exploration Program



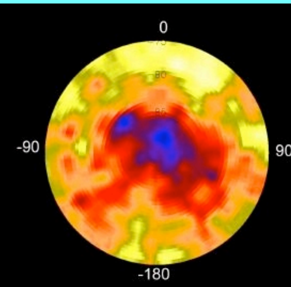
Lunar Orbiter camera



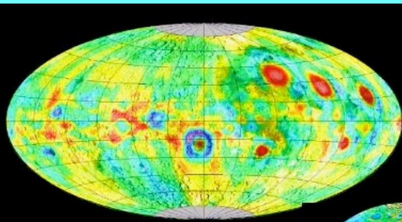
Apollo PanCam



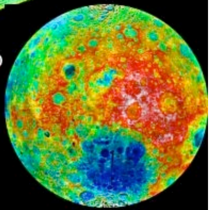
Galileo multispectral imaging of 60% surface



Lunar Prospector elemental mapping



Clementine gravity map & topography



Objective: The Lunar Reconnaissance Orbiter (LRO) mission objective is to conduct investigations that will be specifically targeted to prepare for and support future human exploration of the Moon.

Exploring Earth’s Moon

Topographic data to determine illumination

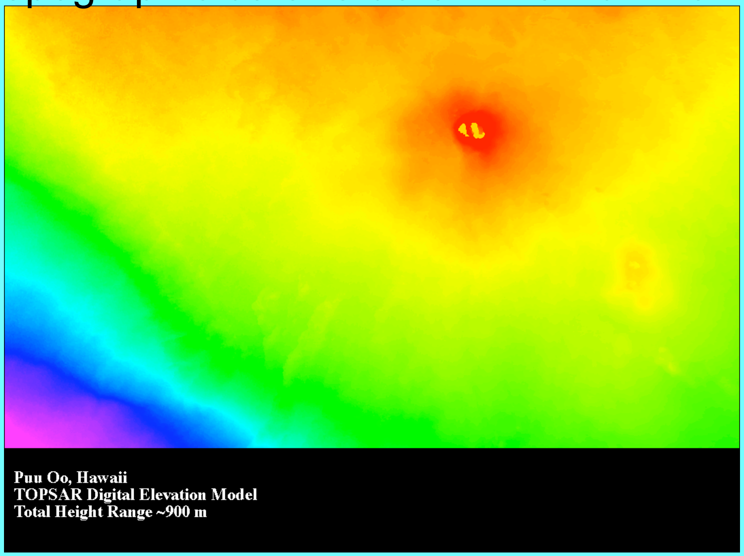
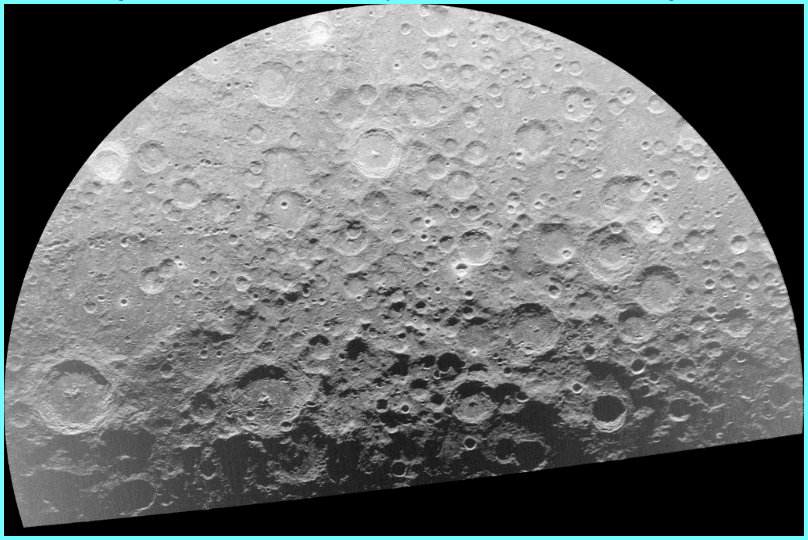
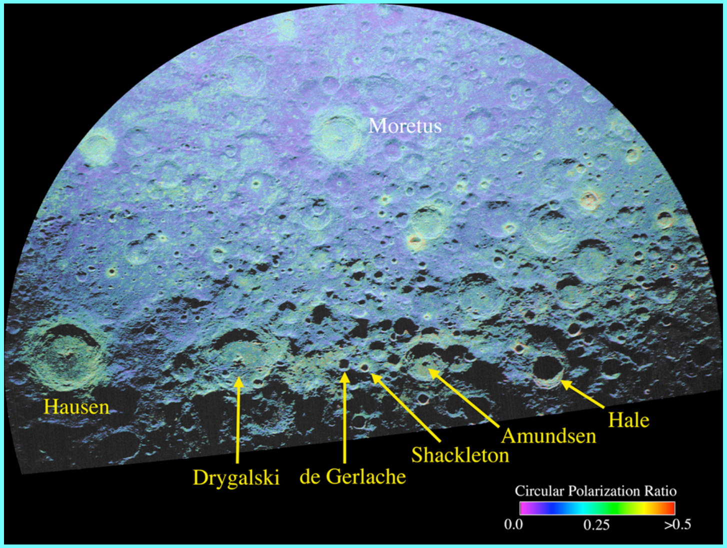


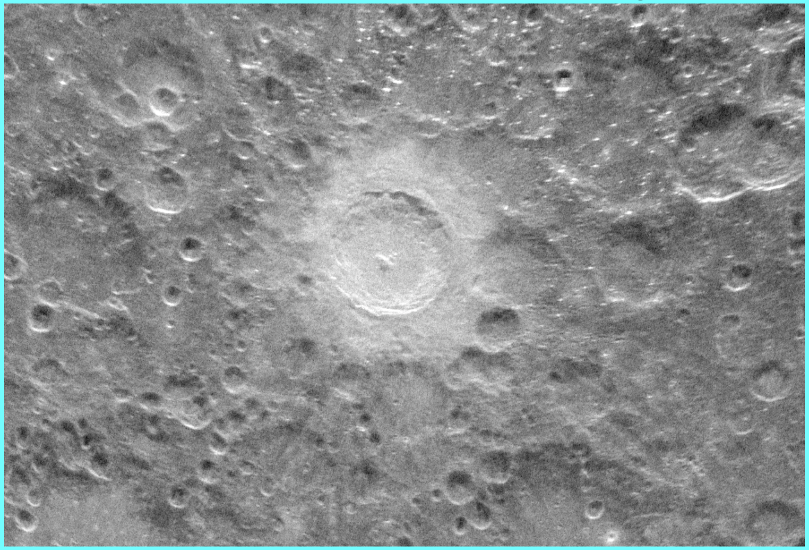
Image permanently shadowed regions



Map polar ice deposits



Characterize terrain for landing sites



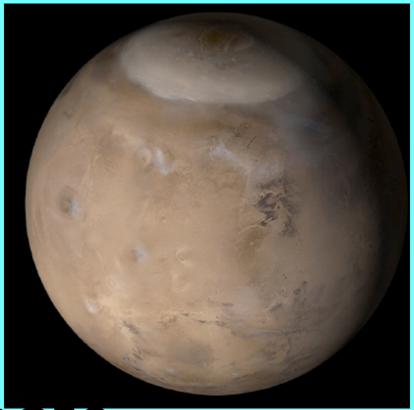
SPACE SCIENCE ENTERPRISE

JPL

Robotic Lunar Exploration

“Starting no later than 2008, initiate a series of robotic missions to the Moon to prepare for and support future human exploration activities”

- *Space Exploration Policy Directive, January 2004*

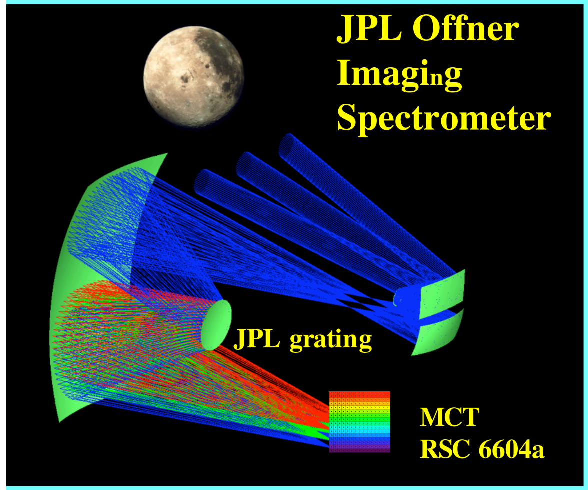


Rationale

- Environmental characterization for safe access
- Global topography and targeted mapping for site selection and safety
- Resource prospecting and assessment of In-Situ Resource Utilization (ISRU) possibilities
- Technology “proving ground” to enable human exploration

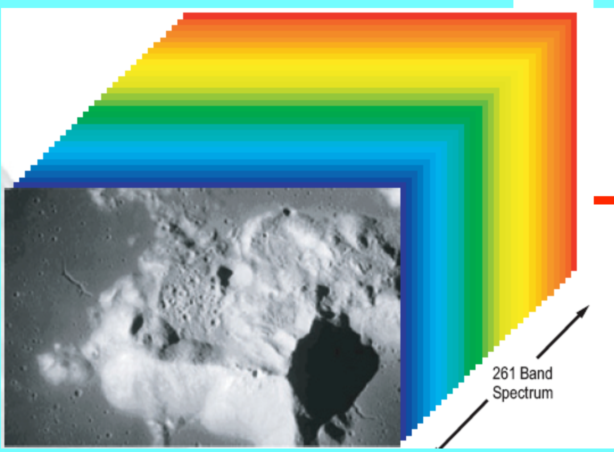
Moon Mineral Mapper (M3)

Uniform Full Range Instrument

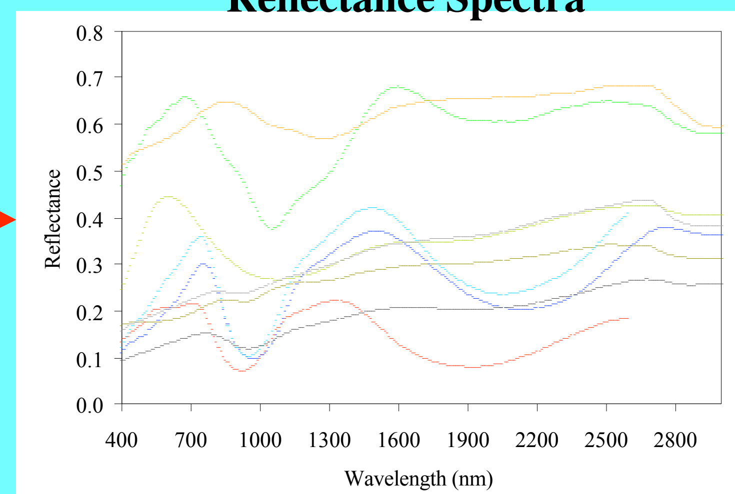


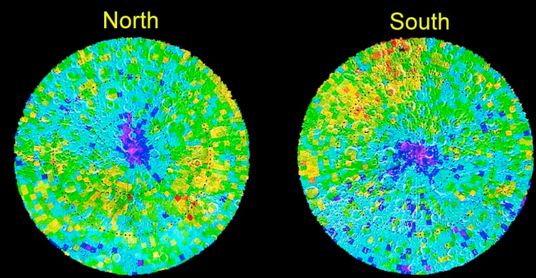
Spectroscopic Analysis to Answer the Science Questions and Meet the Mission Requirements

Calibrated Spectral Image Cubes

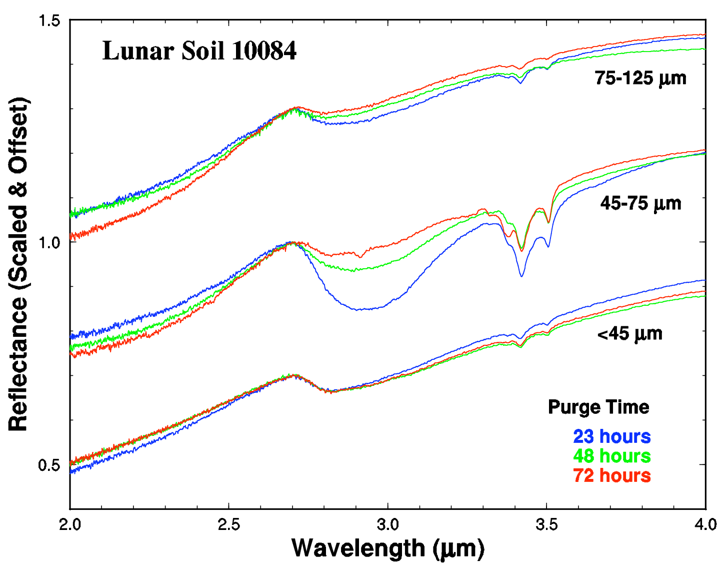


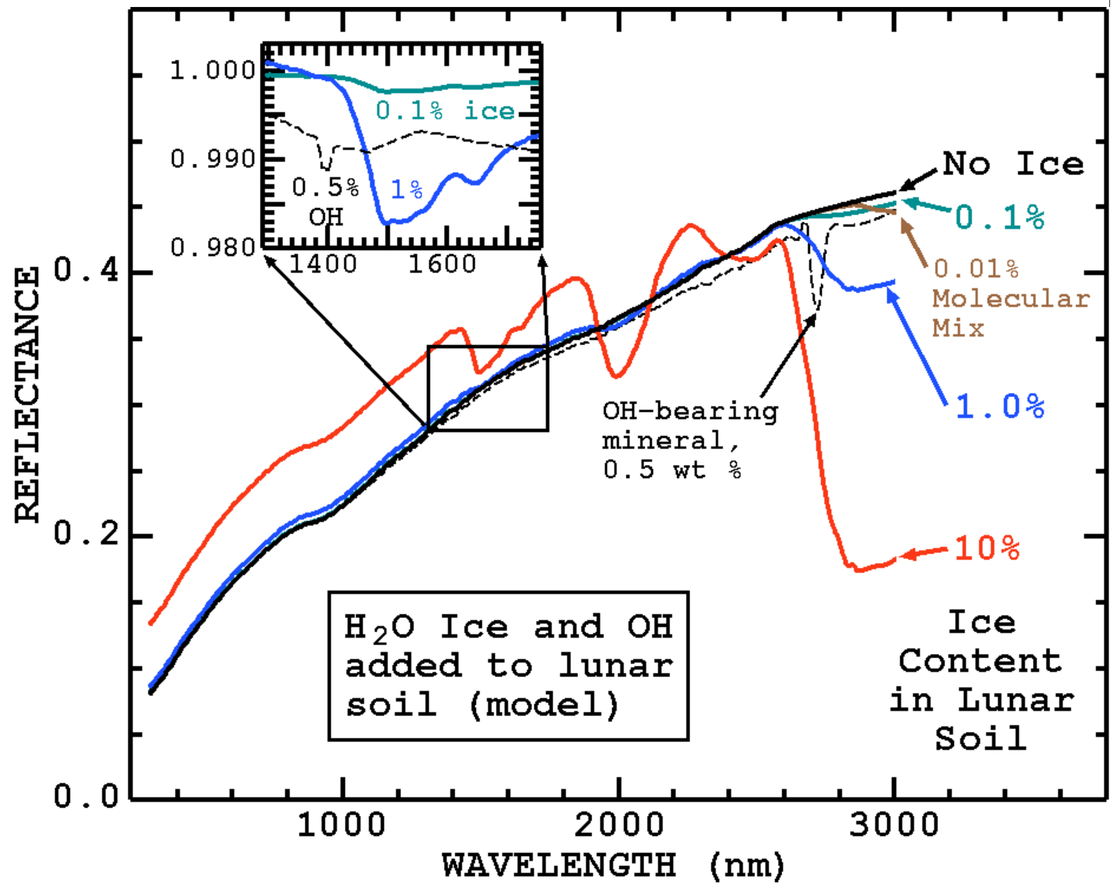
Reflectance Spectra





Lunar Prospector Hydrogen at the poles Water ice?

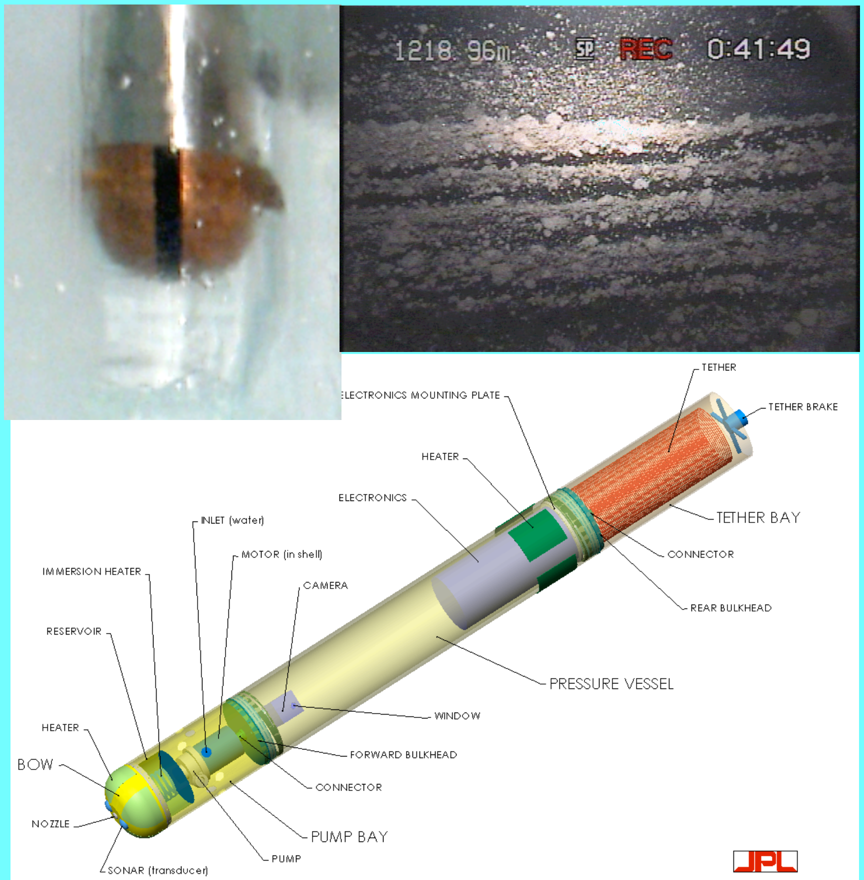




M3 Near-IR spectroscopy can uniquely identify the presence of small amounts of OH or H2O

(surface scattered solar radiation).

Development of Subsurface Active Thermal Probe Technology Testbed



Cryobot

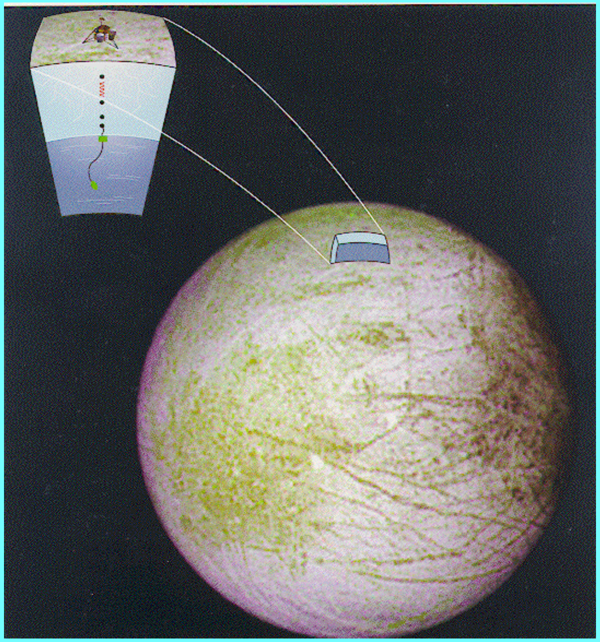
Technology Focus

The Active Thermal Probe technologies have wide applicability to a variety of mission scenarios. By gaining access to the icy subsurface environment, the technology fosters in-situ science exploration. This Cryobot vehicle can take instrument suites to depth through changing stratification. Instruments can include cameras, spectrometers, and in-situ sampling instruments.

Objectives

- Develop a cryobot mobility performance model through ice. Design and build prototype system for laboratory tests. Show ability to travel in clear water ice.
- Testing mobility in ice/sediment environments
- Tethered field operation and acoustic development
- Mobility in ice/vacuum and ice transceiver development

Europa Subsurface Mission



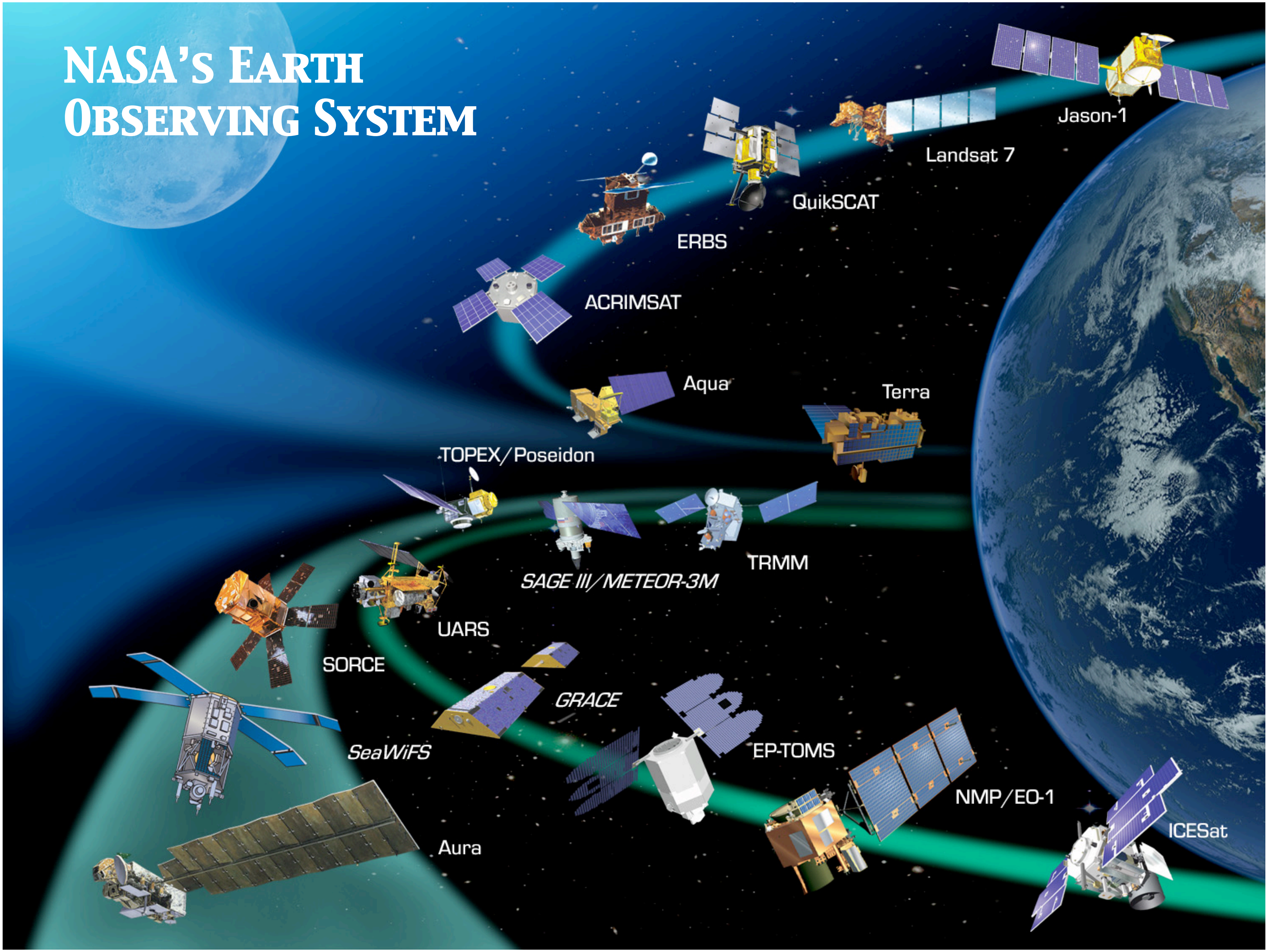
Critical Technology

- Subsurface Access
- In situ instrumentation
- Contamination control

Other Important Technology

- Subsurface navigation
- Communications
- Power sources

- ***Science Objectives***
  - Search for evidence of life
  - Determine the physical and chemical characteristics of ice
  - Determine chemical, physical and biological properties of the ocean
- ***Mission Description***
  - Landing site: Within selected region (thin ice crust or non-deforming ice)
  - Subsurface : Descend 5-30km to the ice/water interface
  - Telecon/Navigation: In-Ice transceivers and Lander telecom
  - Cost: TBD
  - Option: Profile Study of Water, Sediments
- ***Measurement Strategy***
  - Determine composition and temperature as the probe descends through the ice
  - Image features within the ice and ocean
  - Establish ocean observatory at base of ice


NASA'S EARTH
OBSERVING SYSTEM
Jason-1
Landsat 7
QuikSCAT
ERBS
ACRIMSAT
Aqua
Terra
TOPEX/Poseidon
SAGE III/METEOR-3M
TRMM
UARS
SORCE
GRACE
EP-TOMS
SeaWiFS
NMP/EO-1
ICESat
Aura

Calipso and Cloudsat Missions

Will provide key measurements of aerosol & cloud properties needed to improve climate predictions

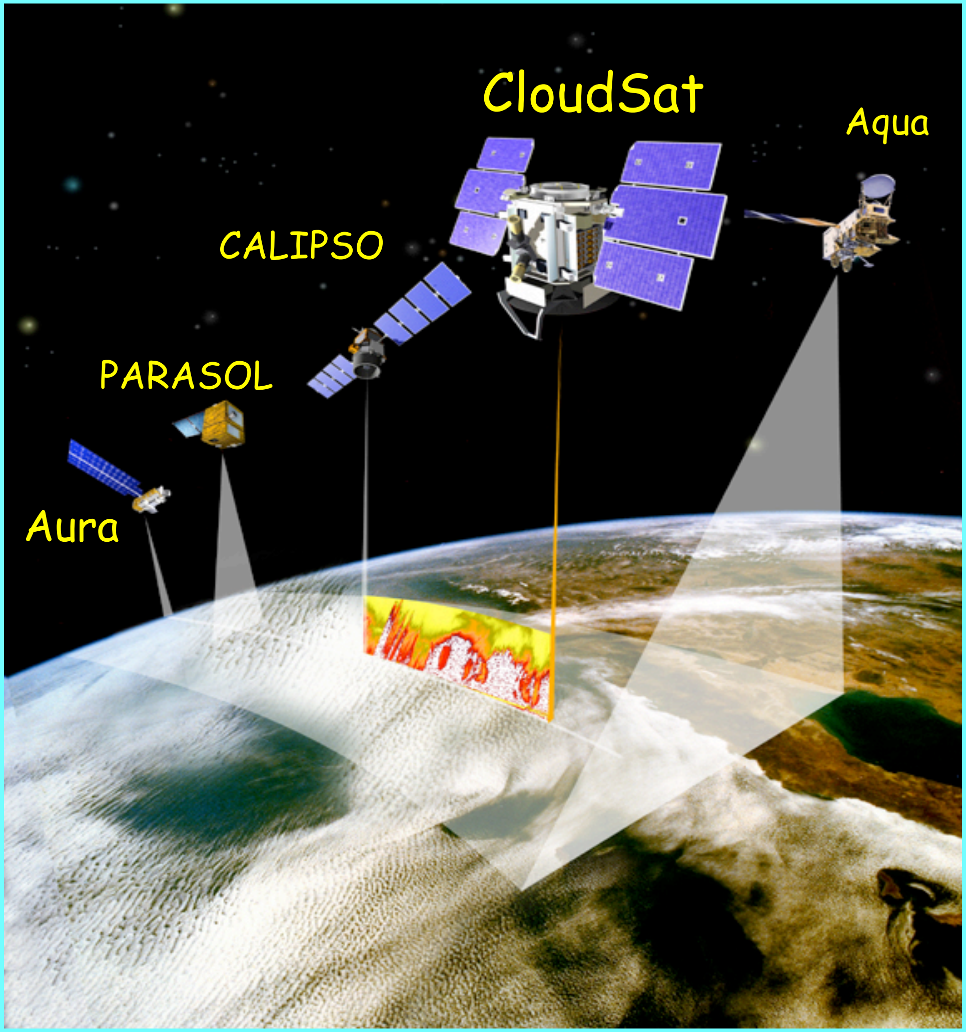
Together, CALIPSO and Cloudsat provide

•A global measurement suite from which the first observationally -based estimates of aerosol direct radiative forcing of climate can be made.

•A dramatically improved empirical basis for assessing aerosol indirect radiative forcing of climate.

•A factor of 2 improvement in the accuracy of satellite estimates of longwave radiative fluxes at the Earth's surface and in the atmosphere.

•A new ability to assess cloud-radiation feedback in the climate system.



Aeronomy of Ice in the Mesosphere (AIM)

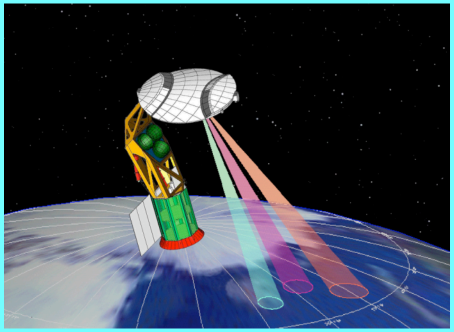
NASA's Small Explorer Mission
to study polar mesospheric clouds
PI: Jim Russell/Hampton University

Launch: September 29, 2006
Prime mission: Two years

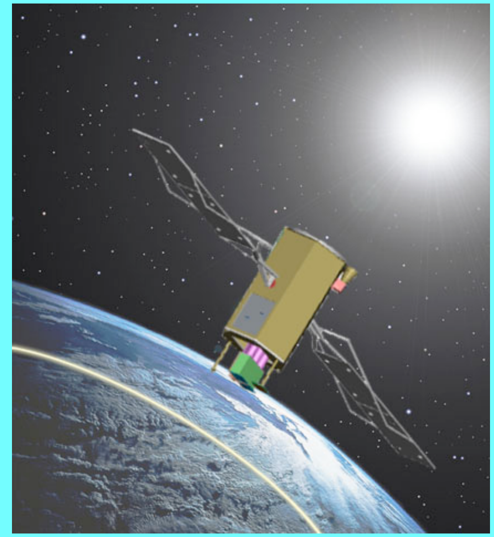
Science Objectives:

- to determine why polar mesospheric (noctilucent) clouds (PMC'S) form and how they evolve
- to understand the relationship between PMC's and the polar mesosphere
- and thus to provide a basis for study of long-term variability in the mesosphere and its relationship to global change

New Capabilities on the Horizon



Aquarius -- Sea surface salinity



Orbiting Carbon Observatory

HYDROS -- Soil Moisture

Innovative Suborbital Platforms -- UAVs, Long-duration Balloons

Big Science Questions

- Ice Thickness
- Snow water equivalent
- Observation of warm glaciers/ice
- Carbon balance – seasonal variations of CO_2 and Methane
- How fast does land ice move?
- Precipitation (not a currently viable measurement)

What Will Be There in 2007-8

In Space

Landsat Series (vis/IR)
GRACE
DMSP Series (passive microwave, et al)
RADARSAT (interferometric SAR)
NOAA Series (vis/IR)
METEOR-3M (passive microwave, vis/IR)
CARTOSAT-1 (high res optical)
CRYOSAT (radar altimetry)
ALOS (SAR)
TerraSAR-X (imaging microwave radar)
RESOURCESAT-1 (high res optical)
METOP Series (scatterometer, vis/IR)
RISAT-1 (imaging microwave radar)
NPP (sounders, vis/IR)
RapidEye (high res optical)

SPOT (through early 2007 –high res optical, vis/IR)
Envisat (through early 2007 –microwave radar, vis/IR)
Aqua (through early 2007 – passive microwave, sounders)
SICH-1M (through 2007 – microwave radar, et al)
SAOCOM 1 (2008-? –imaging radar, vis/IR)
Pleiades Series (late 2008-? - high res optical)

In The Field

- 8 ground stations in Alaska used as validation sites (ALECTRA) since mid-90s for NScat
- Field work across Alaskan North Slope for carbon cycle dynamics study

What is Missing

- Ice thickness measurement
- **Snow-water equivalent**
- **Ground calibration of radar**

What Else Can NASA/JPL Do?

Technology

- **High frequency (Ka/Ku band) SAR for topographic mapping of glaciers and ice sheets**
- **Low frequency radar (CAS) to get direct measure of ice thickness**
- **Interferometric Sounder to measure total global ice sheet volume**
- **AIRSAR using AVIRIS and MASTER**
- UAVSAR to reach larger regions and image ridges in ice

Increased Collaboration

- **Work with ESA for ENVISAT to cover polar regions more thoroughly**
- **NSF for in situ**
- **JAXA for ALOS mosaics**
- **Antarctic Mapping Mission-3 to produce complete high-res image mosaic of Antarctica to examine change and produce first, complete velocity map of the Antarctic Ice Sheet**

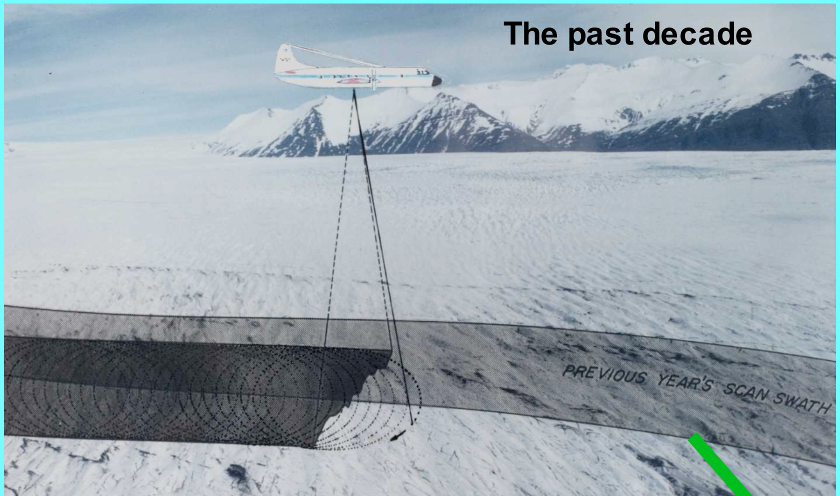
Field Work

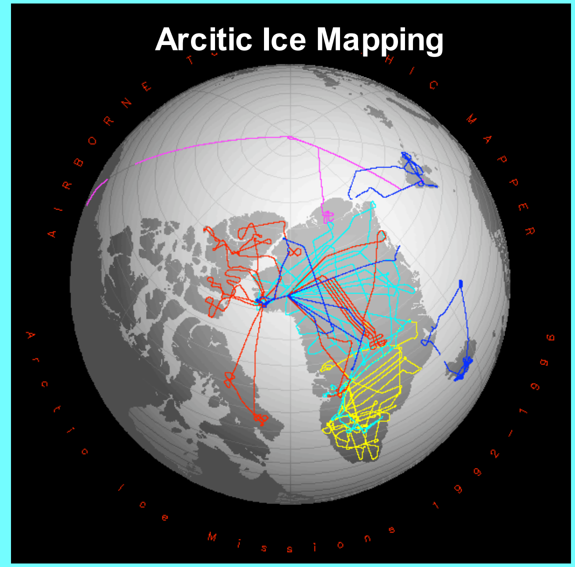
- **PoleNet backbone ground network to support GPS and seismic network; Technology pathfinder to networks on Mars**
- Bedrock crustal motion from GPS ground stations to help interpret GRACE data
- **Ground truth for radar instrument calibration (including geometric)**
- **Corner reflectors for calibration of radar from space**
- **Tumbleweed polar rover for elevation with increased GPS resolution**
- **Polar micro stations for year-round weather, ice melt,precise GPS, & magnetometers**
- Micro-sub for under ice shelf or under lake investigations

Data Fusion

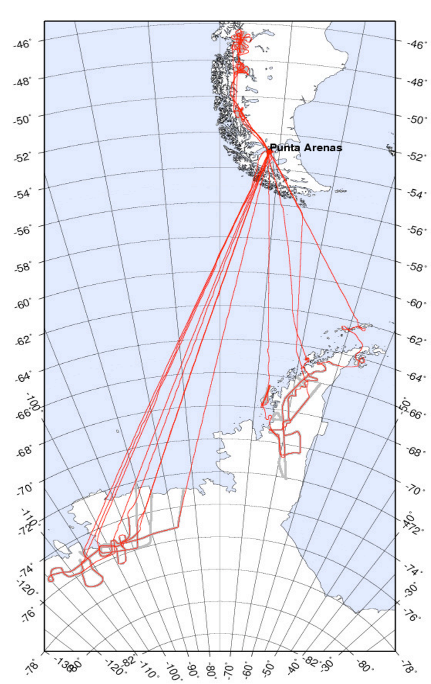
- Velocity maps from RADAR data
- Freeze-thaw and classification of wetlands for ALOS
- Coupled model of Arctic ocean-sea ice-atmosphere (RIMS)

Recent Airborne Mapping of Changes in Ice Cover

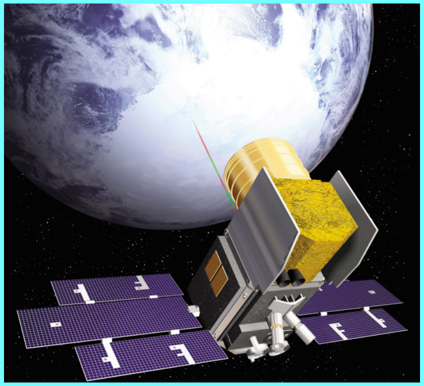


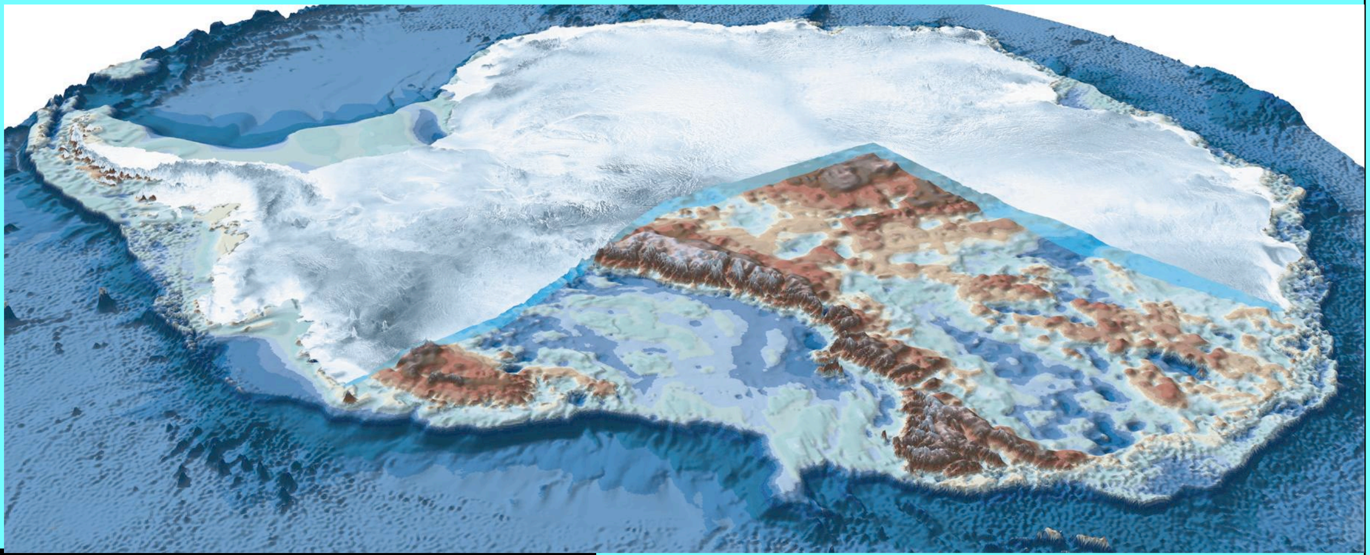


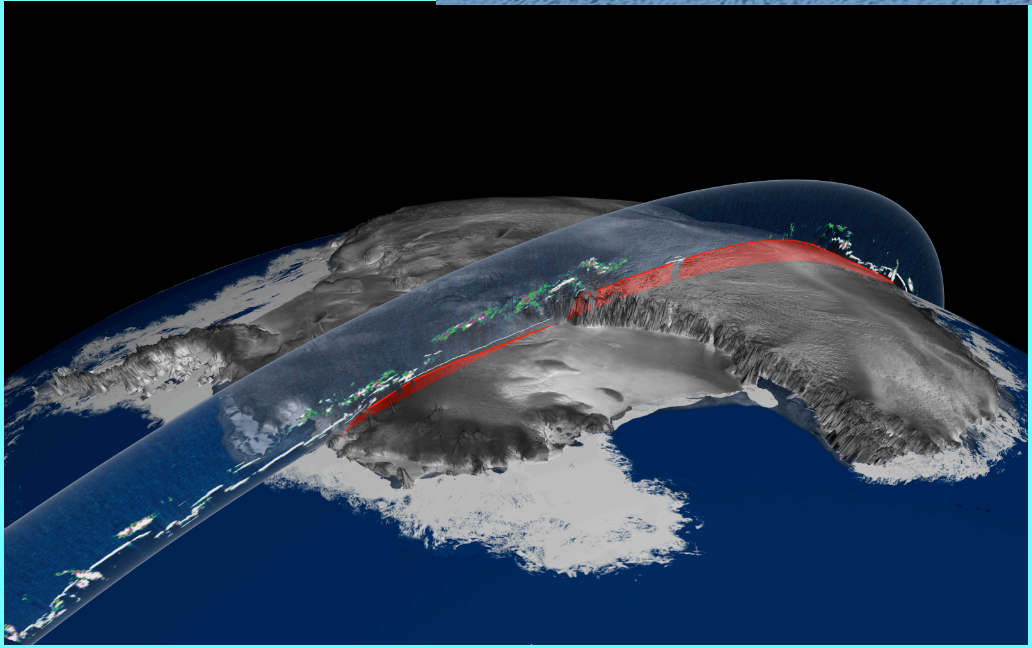
Patagonia and Antarctica surveys

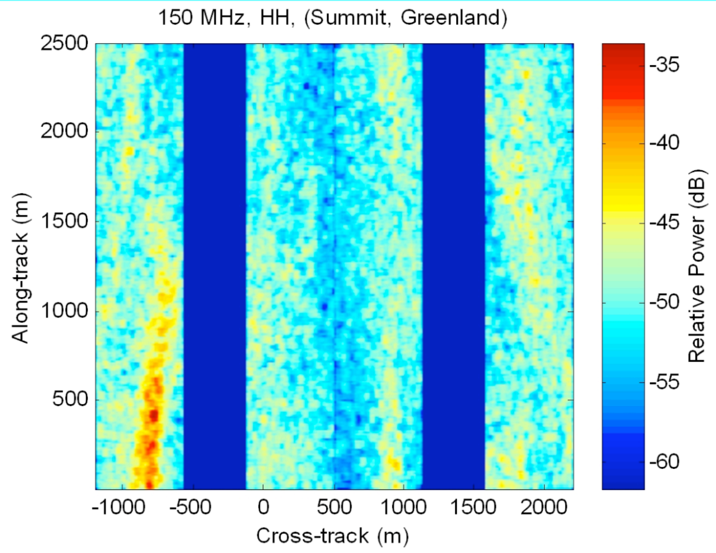


Antarctica - probing the 3rd dimension with lidar and radar



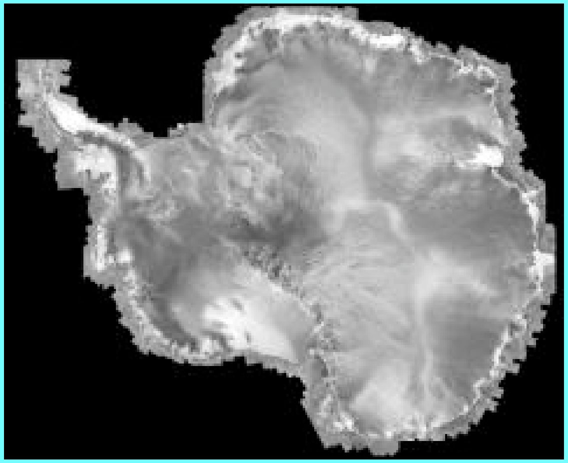




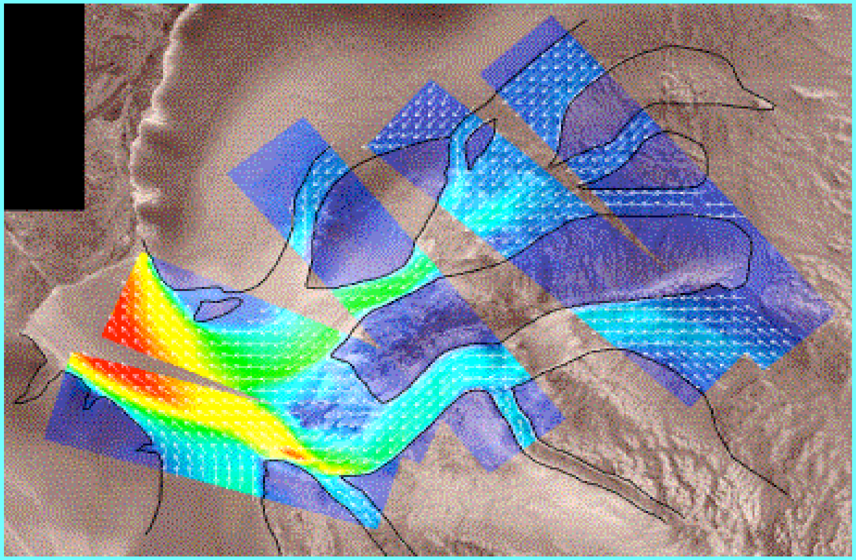


Antarctica: A Snapshot in Time

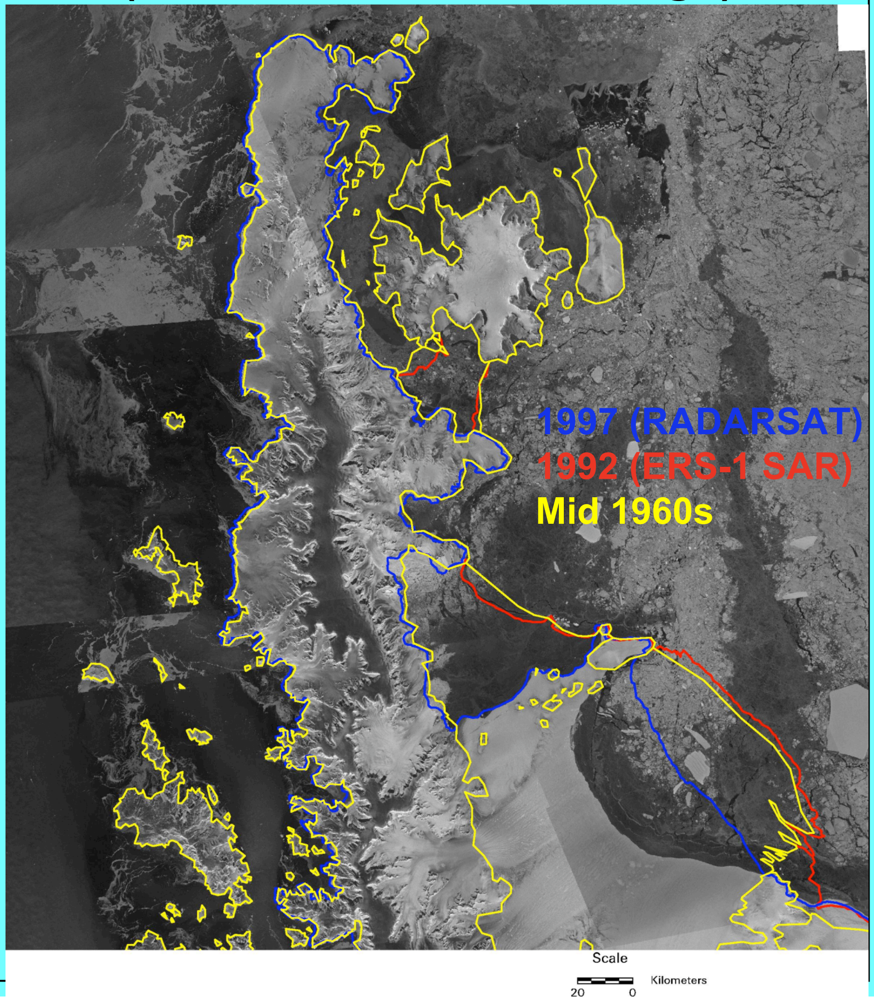
Mapping the Continent



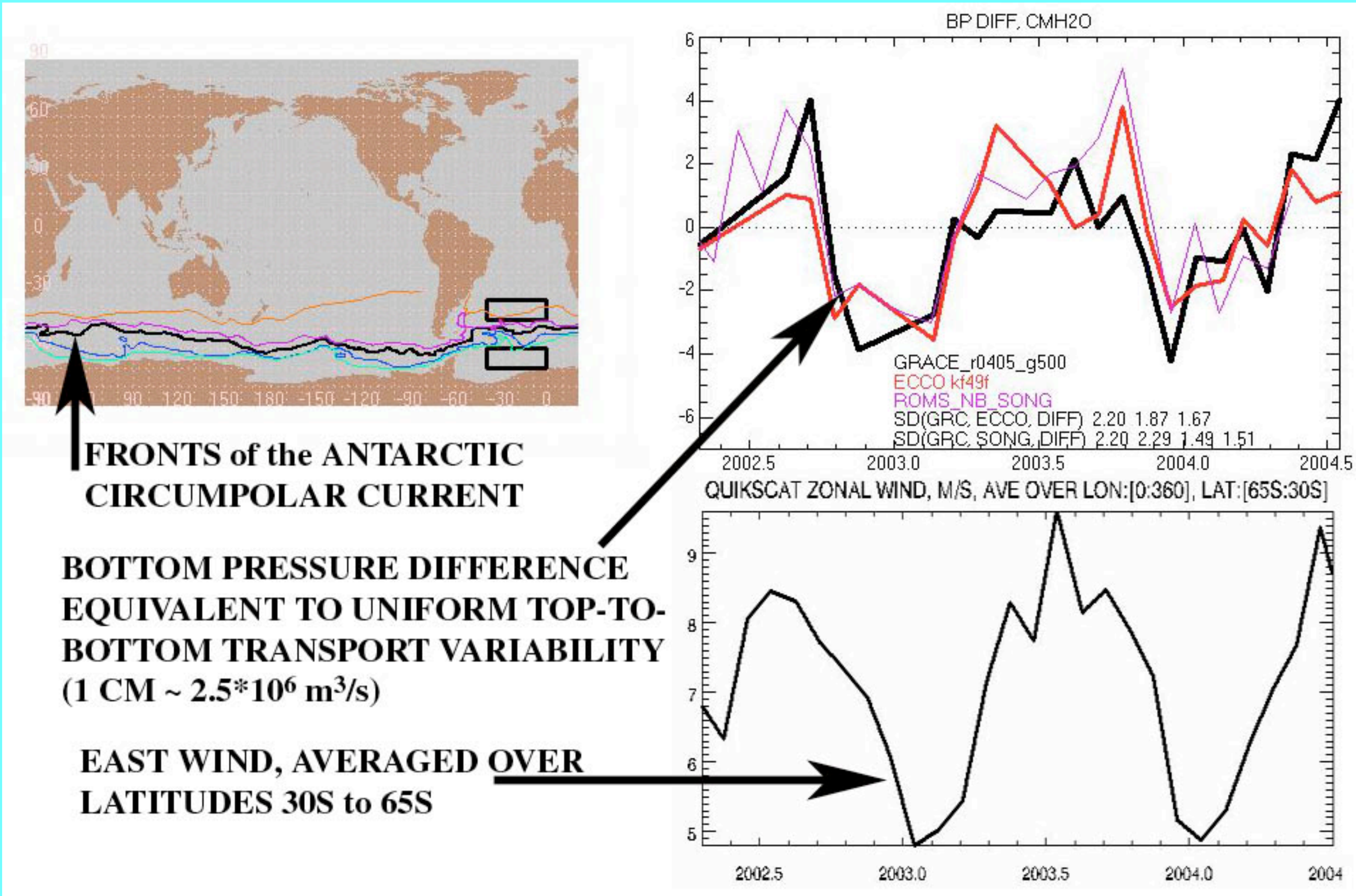
Mapping Velocities



Changing ice margins (2000 RADARSAT-1 Image)

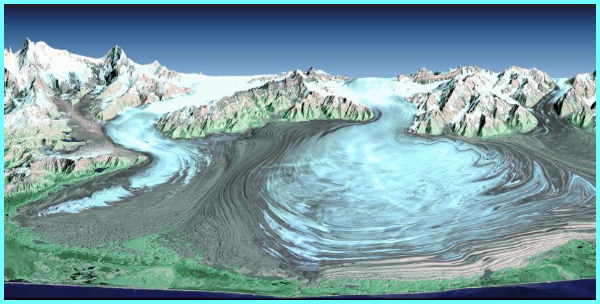


Antarctic Circumpolar Current from GRACE and QuikSCAT



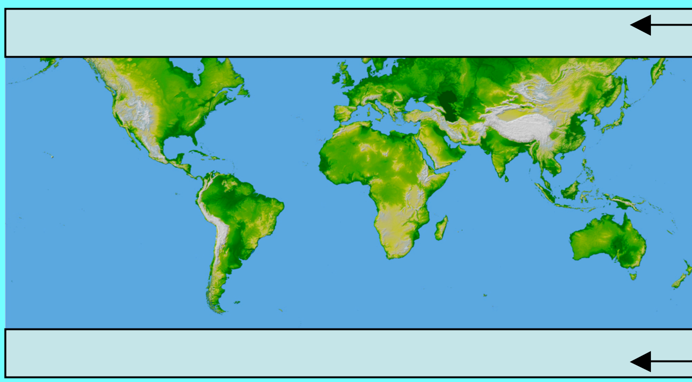
Tandem-X for Ice Applications for IPY: Extend SRTM North and South to complete the Global DEM

Ice Topography Mapping for Change Applications and Mass Balance Studies



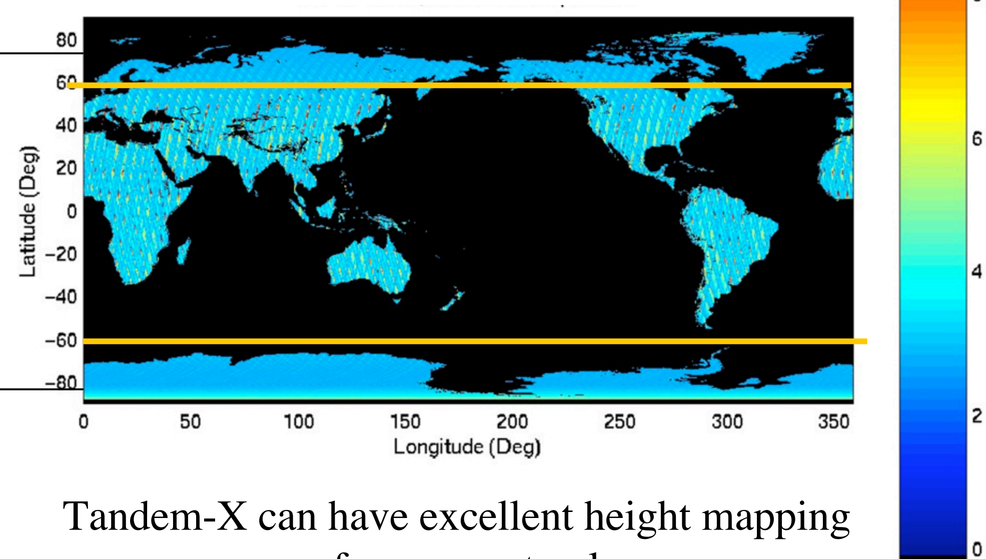
NASA role in Tandem-X

- Polar Interferometric Processing for DEM North of 60° and South of -60° to Polar Science and Applications



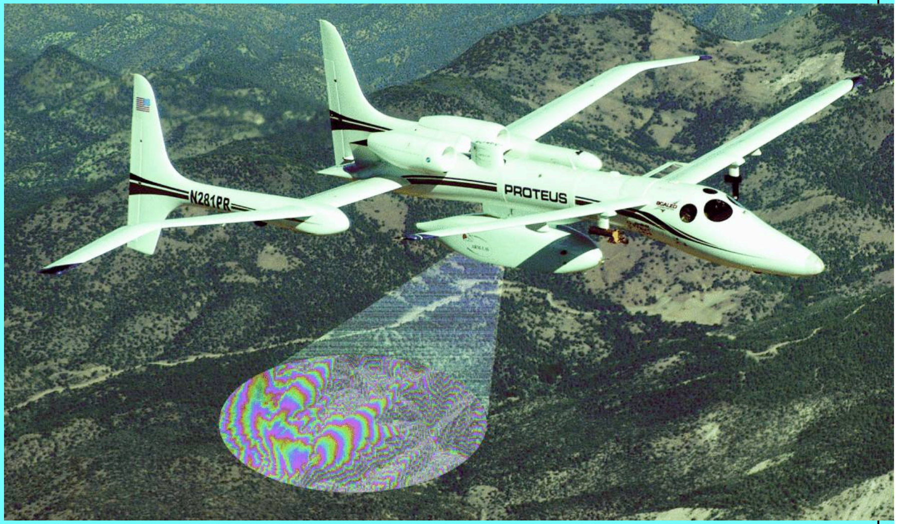
SRTM Near-Global Coverage missed critical polar regions

Expected Height Error for Tandem-X Mission at 10 m resolution



Tandem-X can have excellent height mapping performance at poles

UAVSAR for RPI Deformation Measurements



- UAVSAR is an new radar instrument designed to have a robust repeat pass radar interferometry capability for measuring rapidly deforming surfaces on a UAV.

- Measuring rapidly deforming surfaces such as from volcanoes, earthquakes or certain glaciers with millimeter accuracy.

- Planned inaugural flight on a Gulfstream III in the Fall of 2006 with first science applications beginning in the in late 2007.

  - Major technical innovations inlcude:

    -A polarimetric electronically scanned L-band array and associated radar system that is an easily deployed instrument with radar steering that can be linked to on-board INU.

    -An ability to fly the aircraft based on real-time GPS measurements within a 10 m tube (1 M goal).

In Situ Work

1) Tumbleweed Next round of deployments South Pole, Greenland, Devon Island
Elevation with Increased GPS resolution (<1m)

2) Micro-Gondolas
Multi-day Gondola with science instruments
Deployment with NSF (McMurdo) or BAS Rothera

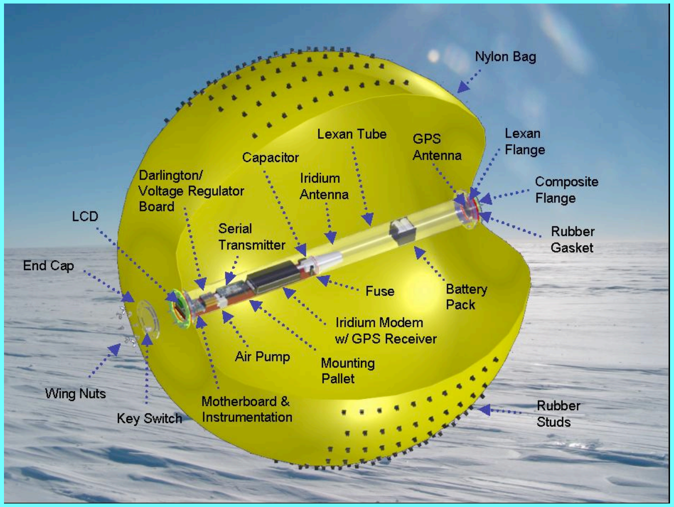
3) Ice Probe
a) Use for Radar (Goggenini) Inclusion/Water Verification
b) Incorporate Spectrometer
c) Upgrade current system with smaller/higher res. camera head

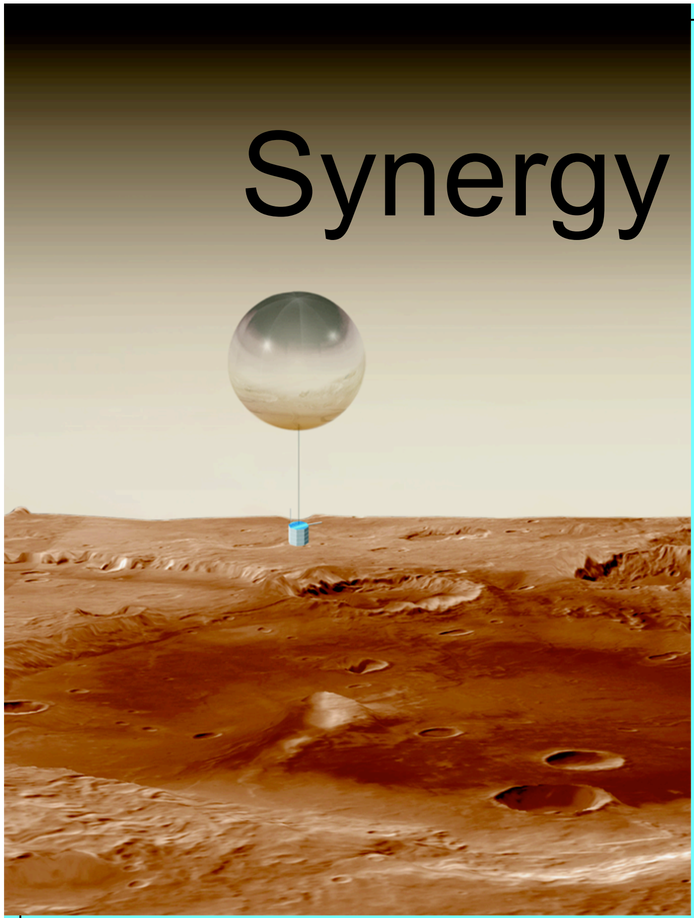
3) Cryobot Mini-Water Drill
Develop a mini water drill for 1-200m drilling with small logistics

4) Micro-Sub
Develop a micro-sub for:
a) under ice shelf investigations
b) Subglacial Lake Investigation

5) Polar Rover
a) Sea Ice Thickness
b) Radar Based Rover

6) Year Round Polar Micro Stations
Can be used for:
a) weather, ice melt, sun radiation
b) precise GPS, Magnetometers





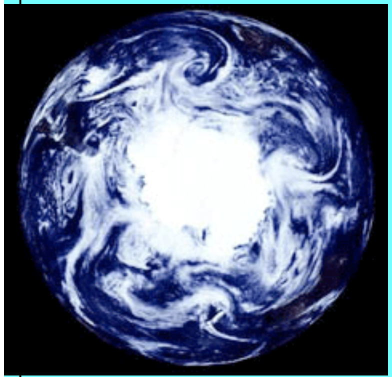
Synergy with Mars Program

- Keen interest in aerial platforms within the future Mars program
- Lightweight, low power and compact instruments **are key to capable systems**

- UAV platforms on Earth can be used as testbeds to demonstrate technology for Mars

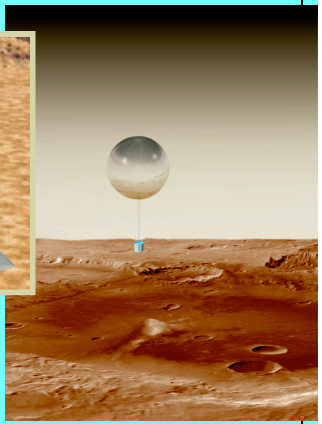
MRO (arrive 2006, primary science mission through 2008)
- Charad sounder to sound the ice sheets
- CRISM hyperspectral imager

Mars Phoenix Mission (Launch in '-07, land in March 2008) to confirm the presence of water in polar regions of Mars



DC-8 Flights of AVIRIS and MASTER over Antarctic Dry Valleys would be analogs of CRISM and THEMIS

Keen interest in aerial platforms within the future Mars program UAV platforms on Earth can be used as testbeds to demonstrate technology for Mars



Mars Pathfinder

Antarctica

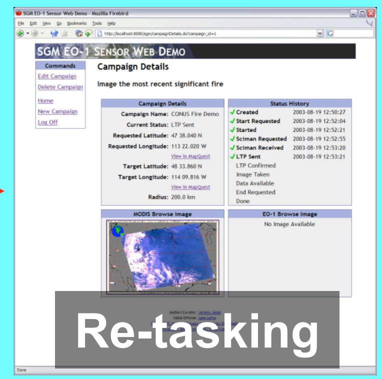
Volcano Sensorweb Example

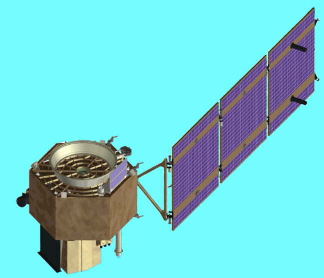
No human in the loop!

Terra/Aqua MODIS Low-Resolution Data (250 m to 1 km/pixel)

Event Detection

In-situ assets

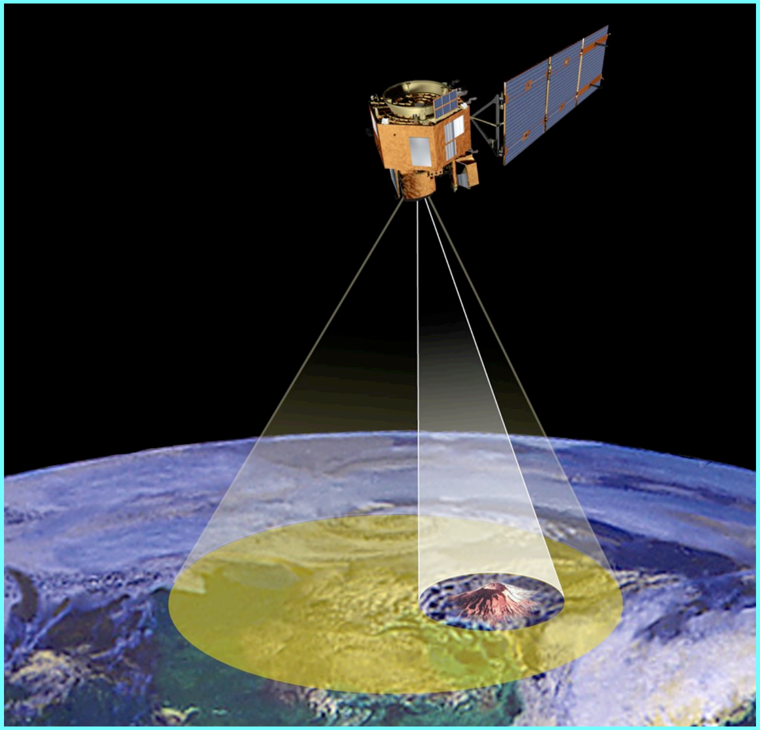




EO-1 Hyperion: Obtain High-Resolution Data of Event (10 m/pixel)

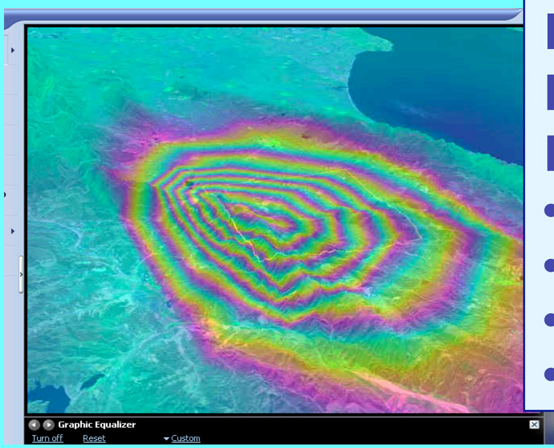
Rapid downlink of relevant data

The EO-1 Autonomous Sciencecraft



- Autonomy software flying onboard Earth Observing One Spacecraft since Oct. 03
- Onboard software enables spacecraft to autonomously monitor and retarget volcanoes, flooding, cryosphere events
- This software has enabled:
  - 100x increase in science return
  - $1.5M/year reduction in operations cost
- In development for MER and Mars Odyssey extended mission
- Co-winner of 2005 NASA Software of the Year Award

Solid Earth Modeling



Technology Accomplishments

Interoperable web portal modeling environment

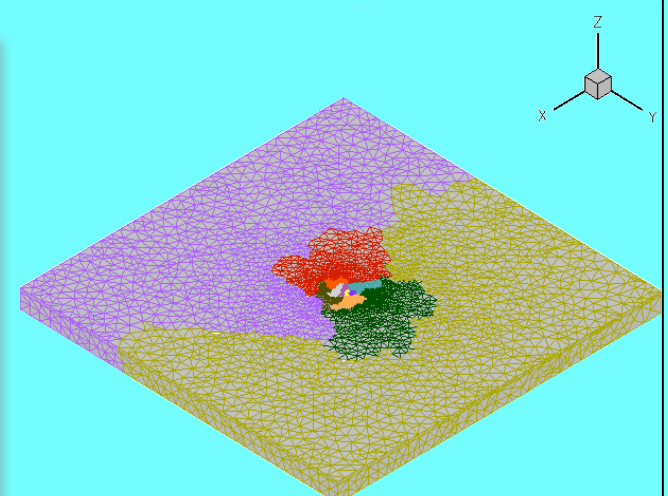
Enables multiscale earthquake modeling

Parallel high performance software:

- **GeoFEST: adaptive finite element software**
- **PARK: fault nucleation boundary element program**
- **Virtual California: models interacting faults**
- **Developing parallel tsunami modeling software**

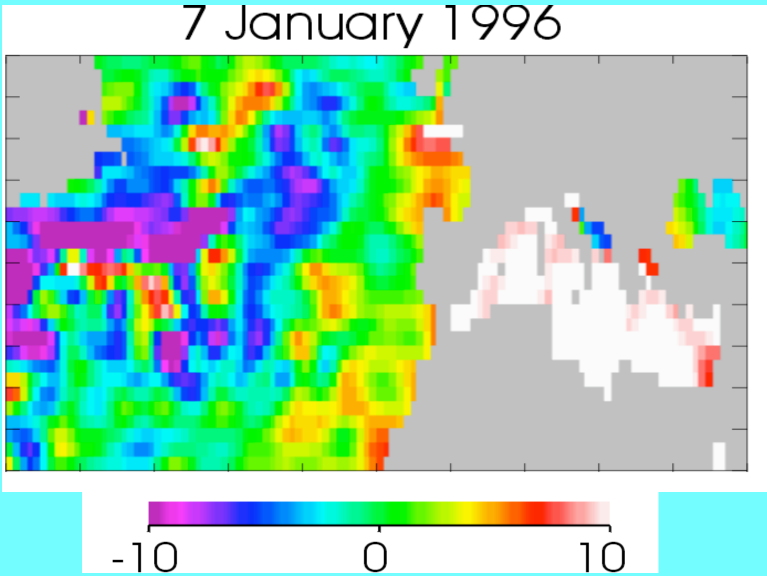
Science Accomplishments/Progress

- **16 out of 17 M>5 earthquakes occurred in regions identified by pattern informatics method**
- **LA basin sediments, and multiple faults control basin shortening**
- **Modeling current observable strain pattern from the 1906 San Francisco earthquake**



ECCO Analysis Reveals Mediterranean Sea Oscillation

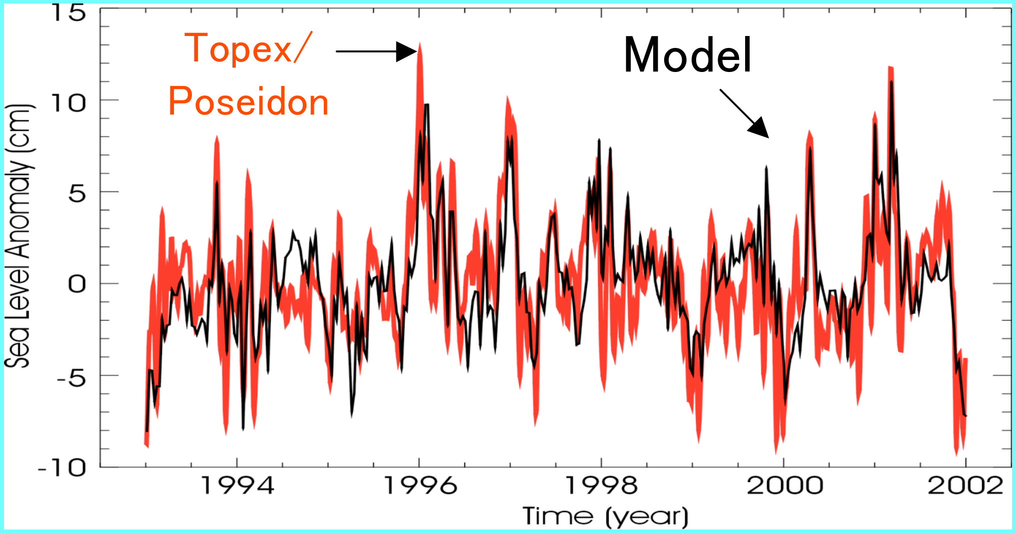
The ECCO model has revealed a new basin-wide sea level fluctuation of the Mediterranean Sea caused by winds in the vicinity of the Strait of Gibraltar.



Variance (cm)

Fukumori, Menemenlis, and Lee (2005, JPO, submitted)

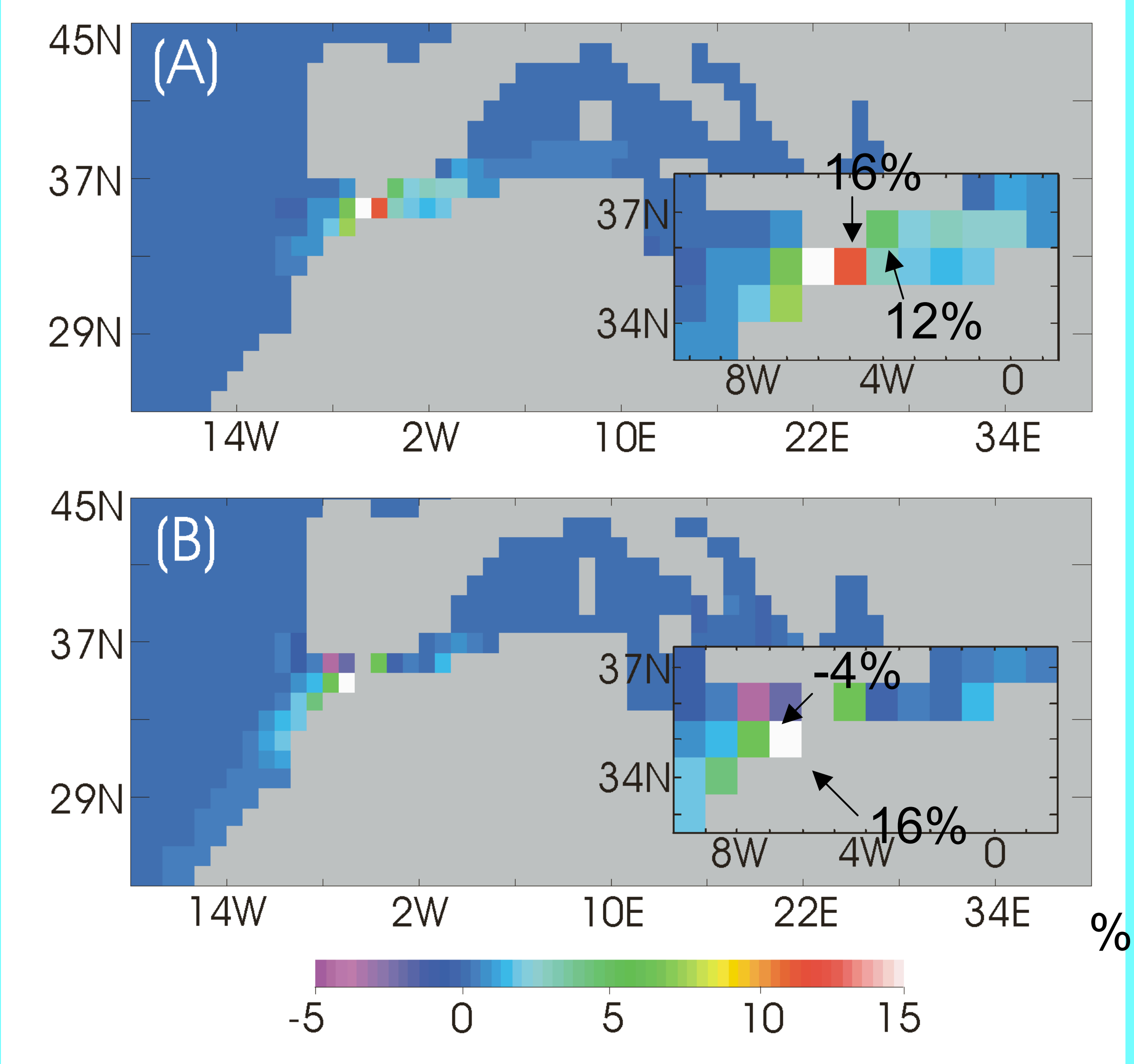
Sea level anomalies (cm) relative to mean annual cycle



Oscillation is due to Winds in Gibraltar Strait

Zonal Wind

Meridional Wind



74%

36%

% of explained variance